TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (cont.)

LIST OF TABLES

I. INTRODUCTION

In water treatment, flocculation is the unit operation in which destabilized particles are given the opportunities to collide with each other and aggregate into floc. Traditionally the mixing necessary for these collisions has been mechanically induced: mechanical mixers in the flocculation basins create velocity gradients in the water being flocculated and the conditions for the agglomeration of particles. However, the energy imparted to a water being flocculated does not necessarily have to come from mechanical mixing. Hydraulic flocculation is also widely used for the purpose of inducing velocity gradients.

Hydraulic flocculation occurs when the turbulence in the water is not the result of mechanical action, but rather of the hydraulic design of the flocculator. The advantages of hydraulic flocculators are that there is less mechanical equipment and less maintenance than with mechanical flocculators, and performance is good at constant flow rates. The disadvantages of traditional hydraulic flocculators are a relatively high head loss and the difficulty of adjusting the system to changing flow rates.

A pilot plant study of buoyant coarse media (BCM) flocculation was conducted at the University of North Carolina at Chapel Hill to determine the feasibility and possible applications of this process. BCM flocculation is a type of hydraulic flocculation in which passage of water through a bed of media provides the turbulence necessary for floc formation. As destabilized particles pass around the media, eddies in the pore spaces between the media create the turbulence needed for particle collisions and flocculation.

Hydraulic flocculation of the type exhibited by BCM flocculation (and also gravel bed flocculation) has several advantages over conventional mechanical flocculation. Operation is simpler since water flow rate, not the speed of the mechanical mixers, is varied. Less mechanical energy is required because mechanical mixers are eliminated. Since these units have a greater height to base area ratio than mechanical flocculation basins, they have the advantages of a smaller footprint and less required space. It is also suggested that media bed flocculators require a shorter detention time than comparably-sized mechanical flocculators.[1]

Media bed flocculators such as the BCM flocculator and the gravel bed flocculator are based on similar design theories. A bed of media is used to create velocity gradients in the interstices between the media. Opportunities for contacts between particles are provided by these interstitial velocity gradients, and the floc which form are captured in the interstices. While there are both upflow and downflow designs for gravel bed flocculators, the BCM flocculator is designed for downward water flow only.

The BCM flocculator tested in this study differs from a gravel bed flocculator in certain critical ways, the most obvious and important being that the media is buoyant. This makes the BCM flocculator easier to clean than a gravel bed flocculator and allows it to be taken out of service for only a short time for cleaning. Cleaning is accomplished by increasing the inlet water flow rate, which expands the bed, releasing floc. A gravel bed flocculator must be taken completely out of service and manually emptied to clean. Tapering of the velocity gradient is achieved in some gravel bed flocculators by incremental changes in the cross-sectional area of the bed. Tapered flocculation is accomplished in the BCM flocculator by inclining one of the retaining walls, providing a continuous change in cross-sectional area of the bed of media. An additional degree of tapering is available with both gravel bed and BCM flocculators by stratifying different sized media within the media bed.

Applications for the BCM flocculator are expected to be in retrofits to flocculation basins in existing water treatment plants and in newly-constructed treatment plants in small communities and developing countries. To increase the hydraulic capacity of existing water treatment plants, it is relatively easy to increase the throughput of rapid mix basins (which usually have excess retention time), sedimentation basins (with plate or tube settlers), and filters (through changing the media size and depth and increasing the loading rate). However, it is often necessary to construct additional flocculation capacity. It is anticipated that the BCM design will allow for the hydraulic capacity upgrade of existing flocculation basins with minimal construction by replacing mechanical mixers with buoyant coarse media and increasing the loading rate to the flocculator.

Small communities and developing countries would have applications for this design because it does not require mechanical equipment which is difficult and expensive to purchase, operate, maintain, and replace. Fewer and less highly trained maintenance personnel would be required since the unit can be cleaned easily by using increased water flow rates and air scouring. Overall, it should be possible to construct these units with less capital and run them with lower operating and maintenance costs than mechanical flocculators.

The objective of this pilot-plant study was, first, to characterize the performance of the BCM flocculator by performing head loss measurements and tracer studies on beds of different types of media. Next, the feasibility of the concept of BCM flocculation was evaluated by conducting flocculation runs using a well defined model water with kaolinite clay as the turbidity source. The final objective of this study was to optimize the overall design and operation of the

BCM flocculation pilot plant using the model water. The optimized configuration could then be tested on a real water at a water treatment plant.

Production of settleable floc from the media bed and head loss across the bed were used to measure the performance of the flocculator. The variables examined during the pilot plant study were media bed configuration, hydraulic loading rates, type of media, media size, layering of media, chemicals and chemical dosages, and water temperature. Subsequent field studies were then undertaken to test the performance of the pilot plant on waters containing both clay and natural organic material, actual water treatment plant chemicals and chemical dosages, and variable water temperature. These field studies were conducted at the Orange Water and Sewer Authority's Jones Ferry Road Plant in Carrboro, NC and at the the Williams Water Treatment Plant in Durham, NC. The results of the field studies are reported elsewhere (Gandley, 1992).

Funding for the study was provided by EIMCO Process Equipment Company of Salt Lake City, Utah. The general contractor for the study was Camp Dresser & McKee Inc. of Cambridge, MA.

The following aspects of the project are discussed in the subsequent chapters:

Chapter 2 discusses the theory and reviews the literature behind this type of flocculator;

Chapter 3 describes the experimental procedures used during this pilot plant study;

Chapter 4 presents and discusses the results of the study; and

Chapter 5 summarizes the conclusions of the study.

II. THEORY OF FLOCCULATION

A. Particles in Water

Raw water entering a water treatment plant normally contains different types of particles, including clays and silts, detritus, humic materials microorganisms, and precipitates of $CaCO_3$, FeOOH, and MnO_2.[2] The range in size of these particles is approximately 0.001 to 0.1 µm for viruses, 0.1 to 1 µm for bacteria, and 0.01 to 10 µm for clays.[2]

The different types of particles in raw water present problems for different reasons. Microorganisms may be pathogenic; humic materials are trihalomethane precursors and can impart color to the water; harmful trace metals and synthetic organic compounds (SOC) can be toxic. Because of their large surface area, particles can offer adsorption sites for microorganisms, humics, trace metals, and SOCs.[3] In addition, the light scattering properties of particles result in the appearance of turbidity in the water. For these reasons, it is important to remove particles from raw water.

B. Particle Removal

The successful removal of particles from water requires that the particles first be destabilized. The destabilization of particles is referred to as coagulation.

1. Particle Stability

Particles in natural water tend to be stable because of either their electrostatic properties or steric phenomena. Electrostatic stability can arise from the reactions of surface groups on particles with water, resulting in these groups either accepting or donating a proton. For example, silica groups on particles are negatively charged at pH greater than 2 and carboxyl groups are negatively charged at pH greater than 4. Another means of attaining electrostatic stability is from the reactions of surface groups with solutes other than protons through specific adsorption of anions and cations. Finally, imperfections within the lattice structure of the particle can cause electrostatic behavior. Steric stabilization results from the adsorption of polymers at the solid-water interface. Depending on the concentration of polymer and particles, the hydrophobic or hydrophilic nature of the polymer (a polymer might also have both hydrophobic and hydrophilic groups), and the type and concentration of electrolytes in solution, this phenomenon can be either stabilizing or destabilizing.[2]

2. Particle Destabilization

There are four mechanisms for the destabilization of colloidal particles: "(1) compression of the diffuse layer; (2) adsorption to produce charge neutralization; (3) enmeshment in a precipitate; and (4) adsorption to permit interparticle bridging."[4] These mechanisms are primarily functions of pH, types of chemicals, the ways in which these chemicals are used (as coagulants or coagulant aids, for example), chemical dosages, and the nature of the colloidal systems involved.[4] Other factors affecting destabilization are the buffer capacity of the water, the hydrolysis equilibria and kinetics of the metal ions and the complexes they form, other ionic species in the water, and chemical equilibria involving the colloids and dissolved substances.[5]

Diffuse double layer compression is an electrostatic phenomenon in which positively charged ions acting as point charges are attracted to the negatively charged colloidal surface and reduce the thickness of the layer of charged species surrounding charged particles.[4] The double layer is thicker in low ionic strength solutions and less thick in high ionic strength solutions. The phenomenon of charge neutralization occurs with the specific adsorption of counter-ions onto the colloid, which reduces the electrostatic repulsion between colloids. Neutralized colloids are able to stick to each other after collisions. Charge neutralization depends on the interactions among the coagulant, colloid, and solvent. It also depends on whether the coagulant is surface active or interacts with water molecules.[4] Enmeshment or sweep precipitation occurs when colloids are trapped within hydrolyzed aluminum or iron precipitate, $Al(OH)_3(s)$ or $Fe(OH)_3(s)$.[4] It is hypothesized that the precipitate begins to form on the particle surface and grows to an amorphous precipitate, trapping other particles in its structure.[3] Interparticle bridging results when chemical groups on a polymer attach to specific sites on the surface of the colloid. The remainder of the polymer molecule extends into the aqueous solution. This unattached portion of polymer is available to attach to the surface of another colloidal particle, forming a floc.[4]

3. Coagulant Chemistry

Aluminum and iron salts form aquometals such as $Al(H_2O)_6^{3+}$ and $Fe(H_2O)_6^{3+}$ in water. These aquometals are hydrolyzed to monomeric, dimeric, and polymeric hydroxy-metal complexes such as $Me(H_2O)_5(OH)^{2+}$, $Me(OH)^{2+}$, $Me(OH)_2^{+}$, $Me(OH)_4^{-}$, $Me_2(OH)_2^{4+}$, and $Me_7(OH)_{17}^{+4}$. These hydroxy-metal species are adsorbed onto colloidal surfaces such as clays. Because they have a high positive charge, they tend to neutralize the negatively-charged clay particle, bringing about particle destabilization. However, the solubility limit of the metal hydroxide is almost always exceeded in conventional water treatment applications, so that the metal is hydrolyzed through a series of reactions from soluble hydroxy-metal complexes, to colloidal/hydroxy-metal complexes, to metal hydroxide precipitates, the last species producing sweep coagulation.[4]

Figure 2-1 illustrates the regions of both charge neutralization and sweep coagulation for aluminum as a function of pH and alum dosage. Figure 2-2 is a similar plot for pH and $FeCl_3$ dosage. The two figures show that at pH of 6.7-7.0 and alum dosages of 20-30 mg/l or $FeCl_3$ doses of 10-15 mg/l, sweep coagulation is the dominant destabilization mechanism for particles suspended in water.

Synthetic polymers used as either coagulants or coagulant aids are constructed of chains of monomers. These polymers increase the strength of hydroxy-metal floc, making the floc more resistant to types of shearing forces that occur in flocculation basins and filter beds. One or more types of monomers may be used. Molecular weight varies and can be as high as 10^7. The chain can be either straight or branched, and the polymer can be nonionic, anionic, cationic, or ampholytic (containing both positive and negatively charged groups) depending on the nature of the monomers comprising the polymer, their functional groups, and solution pH.[4] Cationic polymers affect the use of a metal coagulant by reducing the necessary dosage of the coagulant.[4] Because of the properties of the monomers comprising cationic polymers, the effectiveness of a cationic polymer is less dependent on such solution characteristics as pH, ionic strength, and alkalinity than anionic or nonionic polymers.[2]

C. Flocculation

After particles are destabilized, they are aggregated through gentle agitation of the coagulated water, providing opportunities for collisions between the destabilized particles and allowing for the formation of floc. The term flocculation refers to the process in which particles are transported and given collision opportunities.

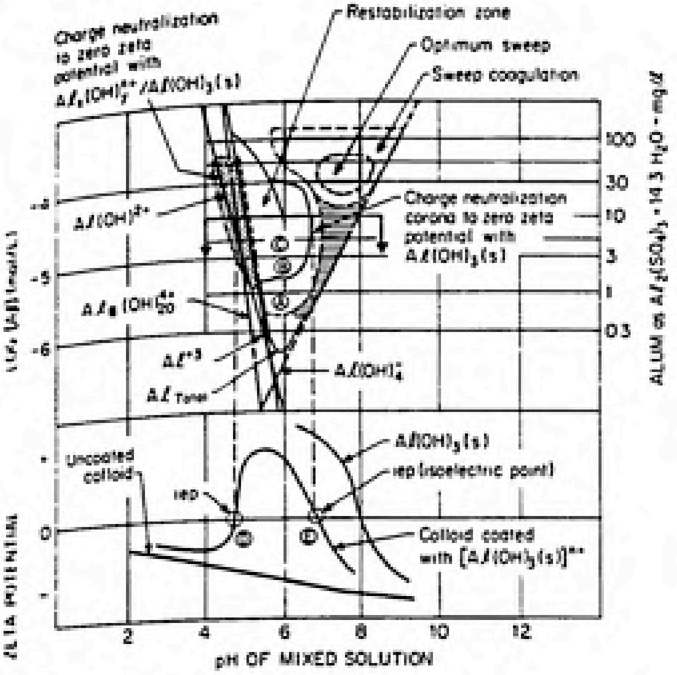


FIG 2-1: THE ALUM COAGULATION DIAGRAM
Source: Amirtharajah and O'Melia, 1990

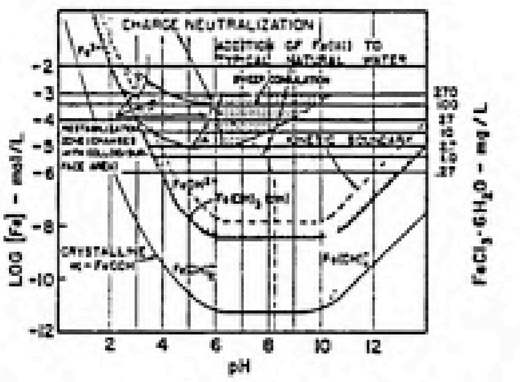


FIG 2-2: THE IRON COAGULATION DIAGRAM
Source: Amirtharajah and O'Melia, 1990

The number of collisions occurring during flocculation in a simplified system of particles of two different diameters is given by the equation

$$N_{i,j} = \beta(d_i,d_j)n_in_j \qquad 2\text{-}1$$

where $N_{i,j}$ = the number of collisions between particles of size d_i and d_j

β = the collision frequency function

n_i,n_j = the number concentration of particles of diameter d_i or d_j

d_i,d_j = the diameter of particles i or j.[3]

The rate at which particles aggregate into floc is given by Smoluchowski's basic equation[2]:

$$\frac{dn_k}{dt} = \frac{1}{2}\alpha \sum \beta(d_i d_j)n_in_j - \alpha\, n_k \sum \beta(d_j d_k)n_j \qquad 2\text{-}2$$

where n_k = the number concentration of particle of diameter d_k formed by the collisions of particles of diameter d_i and d_j.

α = the collision efficiency factor ($0 \le \alpha \le 1$).[3]

The first term of Equation 2-2 refers to the formation of k sized particles from collisions between i and j sized particles. The second term refers to the disappearance of k sized particles as they react with all other sized particles. There is no term for the breakup of particles in this equation.[3]

Collisions between particles can occur through any of three different transport mechanisms: Brownian motion, differential settling, or shear flocculation. Each of these mechanisms has its own collision frequency function, β, the three of which are assumed to be additive.[2]

1. Brownian (Perikinetic) Flocculation

Brownian flocculation results from the random movement of colloids within the fluid caused by the collision of water molecules and particles.[2] These random movements result from thermal gradients within the fluid.

Brownian flocculation is only significant in the transport of particles less than about 1μm.[3] The collision frequency function for Brownian flocculation is

$$\beta = \frac{2}{3}\frac{kT}{\mu}\frac{(d_i+d_j)^2}{d_i d_j} \qquad 2\text{-}3$$

where k = Boltzmann's Constant (1.38×10^{-23} kg-m^2/s^2-°K))

T = absolute temperature (°K)

μ = viscosity (kg/m-s).[2]

2. Differential Settling

Differential settling is the type of flocculation caused by "the sweeping out of small particles by larger ones falling from above."[6] Since these large particles fall faster through the fluid, they catch up to and collide with smaller particles. This type of flocculation is gravity driven and tends to predominate in settling basins rather than in flocculators. The collision frequency function for differential settling is

$$\beta = \frac{\pi g(s-1)}{72\nu}(d_i+d_j)^3\,(d_i-d_j) \qquad 2\text{-}4$$

where g = gravitational constant (9.81 m/s^2)

v = kinematic viscosity (m^2/s)

s = specific gravity of the particles.[2]

3. Shear (Orthokinetic) Flocculation

Shear flocculation results from the existence of velocity gradients at different points in the flocculation basin. The velocity gradient, G, is related to the energy dissipated in the fluid by mixing devises or by the fluid itself as it passes through the chamber. While velocities can be either laminar or turbulent, in water treatment flow is generally turbulent.[2] Since particles in the water will have different velocities at different locations in the flocculation chamber, opportunities for collisions are provided by the velocity gradients. Shear flocculation is the dominant transport mechanism when at least one of the particles is greater than approximately 1μm in diameter and is the principal type of flocculation in practice.[3] The collision frequency function for shear flocculation is

$$\beta = \frac{1}{6}(d_i+d_j)^3 G \qquad 2\text{-}5$$

where G = velocity gradient (s^{-1}).[2]

4. **Velocity Gradient**

The basic formulation of the velocity gradient, G, came from Camp and Stein (1943).[7] Working with the definition of shear stress as a function of both viscosity and velocity gradient, they derived the formula

$$G = \sqrt{\frac{P}{V\mu}} \qquad 2\text{-}6$$

where P = power input to the system (J/s or W)

V = tank volume (m^3)

μ = absolute viscosity (kg/m-s)

Power can be applied to the system through mechanical energy, such as mixing, or through potential energy, such as head.

Camp and Stein, and also Hudson (1965, 1967, and 1981)[8,9,10], found the velocity gradient to be a valuable tool in the evaluation and design of flocculation basins. Their use of the velocity gradient is based on the contention that the rate of flocculation is "directly proportional to the velocity gradient."[7] In conventional mechanical flocculation, the velocity gradient is an important controlling variable, calculated from parameters monitored by operating personnel, such as head loss, torque, or RPMs of the mixers.

Han and Lawler[11] challenged the conventional importance placed on the velocity gradient by making corrections to the standard rectilinear model of particle collisions. The approach they took incorporated the "short range forces and changes in fluid motion as particles approach one another."[11] Solving

Smoluchowski's basic equation (Eq. 2-2) without making the simplifying assumptions that all particles in the system are the same size or that shear flocculation is the dominant process, they considered "hydrodynamic interactions," which are the effects on molecules of water having to be displaced as particles approach each other,[11] and van der Waals attractive forces. A third force, the repulsion force caused by the diffuse layer, was disregarded because most particles are chemically destabilized prior to flocculation. The effect of taking these forces into account is that particles approach each other in a curvilinear rather than a rectilinear path.

The curvilinear model solved by Han and Lawler indicated that Brownian flocculation and differential settling are actually more important and shear flocculation somewhat less important than usually considered in conventional flocculation. Based on their analysis, they suggested that velocity gradients within the flocculation basin lead to fewer collisions than predicted by earlier investigators, but that they are still important in keeping particles in suspension so that more collisions can occur through any of the three mechanisms.

D. Types of Flocculators

1. Mechanical Flocculators

Mechanical flocculation is extensively used by water treatment plants due to the flexibility inherent with its design. However, considerable technical and financial resources must be available for the purchase, operation, and maintenance of this type of flocculator. Typical hydraulic retention times for mechanical flocculation basins are 15 to 30 minutes, and surface loading rates are 4 to 8 GPM/ft^2.[3] Mechanical flocculators use mechanical mixers to impart a velocity gradient to the water. Depending on the type of plant in which the flocculation occurs, either horizontal or vertical shaft mixers are used. Horizontal mixers produce a lower velocity gradient (up to 50 s^{-1}), which in turn produces a larger, easily settleable floc. These types of mixers are used in conventional treatment plants with sedimentation basins. The major disadvantage of horizontal shaft mixers is that their bearings and packings are under water, resulting in higher maintenance costs. Vertical shaft mixers can impart a velocity gradient of up to 100 s^{-1} to the water. These types of mixers produce the smaller, stronger floc needed in direct filtration plants where floc penetration into the filter is important.[3]

Most mechanical flocculators are designed to taper the velocity gradient from a high value at the beginning of the flocculation basin to a lower value at the end of the basin. The theory behind tapered flocculation is that progressively less energy should be imparted to the water to prevent previously-formed floc from being broken up or sheared apart.

For mechanical flocculators, tapered flocculation is accomplished by constructing multiple flocculation basins in series and providing a lower velocity gradient in each successive basin. Both Montgomery[3] and Hudson[10] recommend two or three flocculation basins in series, not only to establish a lower velocity gradient in each successive basin, but also to reduce short-circuiting. Mixers are usually provided with variable speed drives so that the velocity gradient in a flocculation basin can be easily adjusted. Typical velocity gradients are 50 to 75 s^{-1} in the first basin, tapering to approximately 10 s^{-1} in the last basin.[3]

2. **Hydraulic Flocculation**

Hydraulic flocculators impart flow variations to the water to create the velocity gradients and agitation which promote the particle collisions necessary for flocculation. There are three general types of hydraulic flocculators: baffled channel, jet action, and media bed flocculators. The baffled channel and media bed flocculators are the most common types.[1] Each of these flocculator types have the advantages, compared to mechanical flocculation, of not requiring mechanical equipment to induce velocity gradients and of requiring lower capital, operating, and maintenance costs. Hydraulic flocculators are widely used in developing countries for the above reasons and because they can often be constructed by relatively cheap local labor using locally-available material.[1] The disadvantages of hydraulic flocculation relative to mechanical flocculation are that it is less flexible in response to changes in water quality, the flocculation parameters are dependent on water flow rate and cannot be varied independently, head loss across the flocculator is often a large portion of available head, and cleaning the unit can be costly and time consuming.[1]

a. **Baffled Channel Flocculators**

Baffled channel flocculators impart the required velocity gradients to the water by causing reversal of flow as water turns corners established by the baffles. Horizontal flow baffled channels are often preferred to vertical flow because head loss can be varied easily by inserting or removing baffles, and cleaning is facilitated by sloping the bottom of the basin. However, horizontal channels require more land than vertically baffled channels. Also, the cleaning problem associated with vertical flow can be addressed by drilling holes in the bottom of the vertical baffles to prevent settling. In baffled channel flocculators, tapered flocculation is accomplished by varying the number and spacing of the baffles. Retention time in these types of flocculators is from 15 to 30 minutes. The velocity gradient is tapered from approximately 100 to 10 s^{-1}. Hydraulic capacities are typically greater than 2.5 MGD.[1]

b. Jet Action Flocculators

Jet action flocculators impart turbulence to the water to be flocculated by using the velocity of the influent water to change the direction of flow. There are two main designs for these types of flocculators: heliocoidal-flow and the Alabama type. Heliocoidal-flow flocculators use the velocity of the influent water and the size and shape of the flocculator to impart rotational motion to the water. This can be accomplished through either a series of rectangular chambers or a stair-step design. The Alabama type flocculator uses an inlet pipe aimed upward in each chamber to impart an initial upward flow to the water before it flows down into the pipe toward the next chamber. Retention times are from 15 to 25 minutes. These types of plants are hydraulically rated for flow rates as low as 0.8 MGD.[12]

c. Media Bed Flocculators

Media bed flocculators, also called contact flocculators, use the water pathways through the interstitial spaces formed by the media to provide contacts between particles, contacts between particles and the media, and contacts of particles with floc retained in the bed.[12] These types of flocculators capture and store floc within the interstitial spaces of the bed and periodically release floc into the flocculator effluent. The velocity gradients produced by media bed flocculators are a function of the media size, the flow rate, the cross-sectional area of the bed, and the head loss across the bed.[1]

Gravel bed flocculators are the most common type of media bed flocculators. These types of flocculators use a bed of gravel to establish velocity gradients within the spaces between the gravel. Typical designs for gravel bed flocculators are shown in Figure 2-3 (downflow type) and Figure 2-4 (upflow type). Bed depth is usually from 5 to 10 feet.[12] Tapered flocculation is achieved by varying the cross-sectional area of the bed and by stratifying the

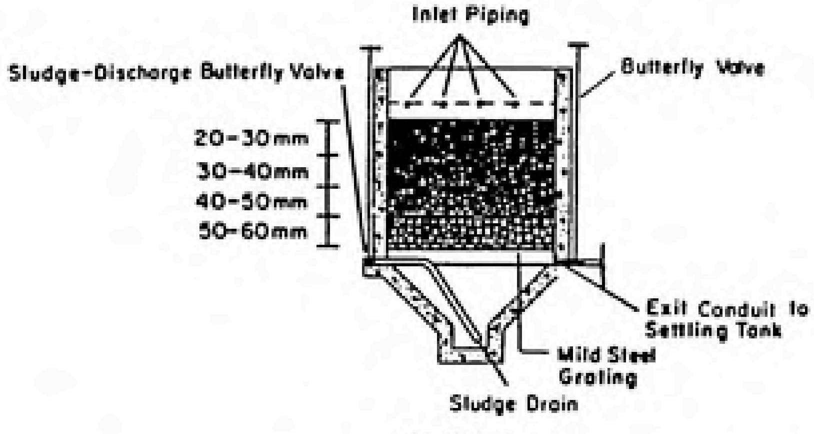


FIG. 2-3: DOWNWARD-FLOW GRAVEL BED FLOCCULATOR
Source: Okun and Schulz, 1984

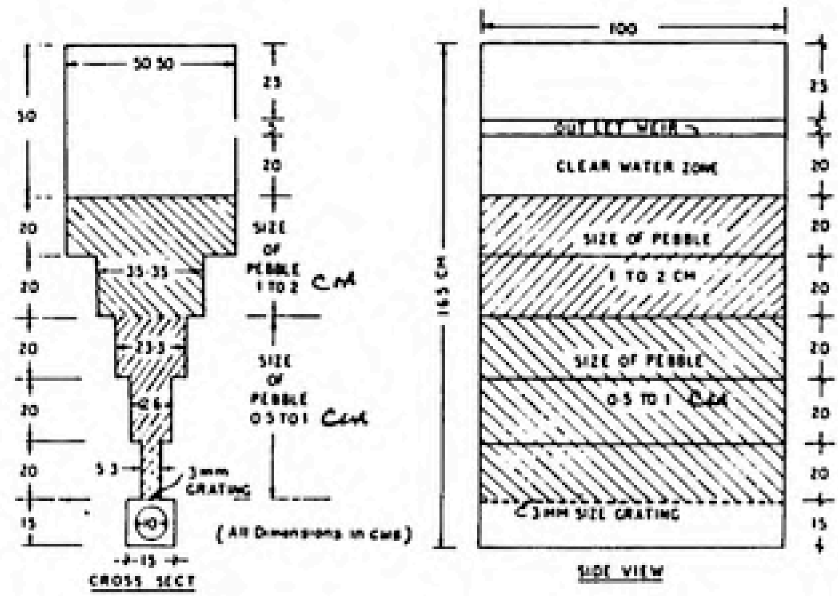


FIG. 2-4: UPWARD-FLOW GRAVEL BED FLOCCULATOR
Source: Okun and Schulz, 1984

bed with different sizes of media. These types of flocculators typically have hydraulic ratings of less than 1.3 MGD. Because there is little short-circuiting and the entire bed is used to form floc, retention times are usually in the range of 3 to 5 minutes[1], compared to 15 to 30 minutes for mechanical flocculators.

Head loss for gravel bed flocculators vary not only with water flow rate, but also with the amount of floc captured in the bed. As floc is deposited in the bed, the porosity of the bed decreases and the head loss increases. The velocity gradient is affected by head loss and the configuration of the media bed. By varying the cross-sectional area of the bed and layering different gravel sizes within the bed, the velocity gradient can be tapered. Velocity gradients range from over 100 s^{-1} at the beginning of a tapered media bed to around 35 s^{-1} at the discharge of the bed.[12]

The two main disadvantages of gravel bed flocculation are: (1) difficulty in sludge collection and removal, and (2) fouling or plugging of the bed. Sludge collection and removal are facilitated by either designing a bottom hopper in downflow flocculators or a grid of perforated drainage pipes on top of the bed in upflow flocculators. Fouling and plugging of the gravel bed, whether because of excessive floc build-up or from biological growth, can usually be addressed through drainage and backwash.[1]

E. Buoyant Coarse Media (BCM) Flocculator

The BCM Flocculator is similar to other media bed flocculators in certain aspects. Velocity gradients are established by flow through the interstitial spaces of the media. Contact opportunities are provided in the interstices between particles, particles and media, and particles and floc retained in the bed. BCM flocculation is designed to allow the velocity gradient to be tapered by inclining the walls of the flocculator and by stratifying the media by size within the bed. Head loss across the bed is a function of both flow rate and the amount of floc stored within the bed.

The most fundamental difference between the BCM flocculator and gravel bed flocculators is that the media is buoyant. This allows the BCM flocculator to be cleaned more easily through expansion of the bed with an increased water flow rate and/or air scour. If an increased flow rate is to be used to clean the bed, this can be done with influent water rather than with flocculated water. Gravel bed flocculators, on the other hand, must be taken completely out of service and totally emptied to clean the media. The angle of the retaining walls of the BCM flocculator is intended to be easily adjusted to allow changes to be made in the tapering of the velocity gradient. This addresses the disadvantage of many hydraulic flocculators which cannot respond easily to changes in flow rate and which cannot adjust operating parameters independent of flow.

Another type of flocculator similar to BCM flocculator is the Haberer process.[13] In the Haberer process, water flows up through a bed of polystyrene media, in which sizes from 1.3 to 2.5 mm (0.05 to 0.10 inch) have been used. This compares to media sizes of 3/8 inch to 3/4 inch used in the BCM flocculator. Cleaning is accomplished by a downflow backwash of three to five minutes. During backwash of the pilot-scale Haberer plant, media bed expansion of 25 to 30 % has been observed.[13] In the Haberer process, a side stream from the effluent of the flocculator is recycled to reduce the usage of coagulants. Two full-scale units have been constructed using this process: one of 4.0 MGD and the other of 9.9 MGD nominal capacity. Using bed depths of 3.3 to 4.9 feet, these units have experienced head losses through the media bed of up to 800 mm (2.6 feet).[13] By comparison, the BCM flocculator used media beds of five to six feet and experienced head losses of approximately 300 mm (one foot).

Details of BCM flocculation and a more complete description of the BCM flocculator are provided in Chapter III.

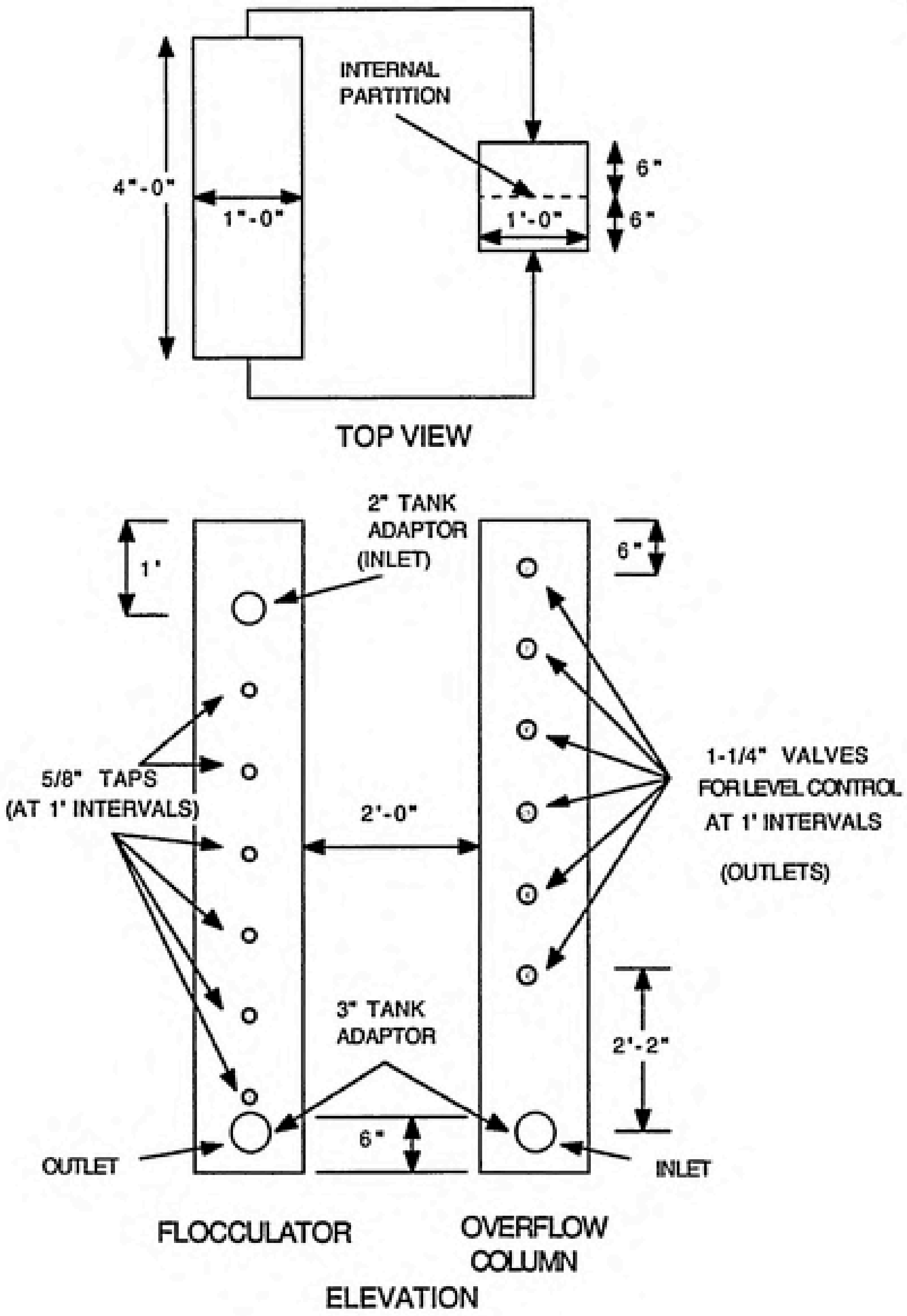
III. EXPERIMENTAL PROCEDURES

A. Description of Pilot Plant

The pilot plant which was tested in this study consisted of a rectangular acrylic tank filled with buoyant media (the flocculator) and an overflow column for controlling the water level in the flocculator. The physical relationship between the flocculator and the overflow column is illustrated in Figure 3-1. The design of the pilot plant allowed for parallel testing of two different beds of media, each with its own overflow column, when the flocculator was set up in the straight bed configuration. When the flocculator was set up in the tapered bed configuration, only one side of the overflow column was used.

The flocculator was constructed from one-inch thick acrylic. The dimensions of the flocculator were four-feet long by one-foot wide by eight-feet high. Six 5/8-inch holes at one-foot intervals were tapped into each side of the flocculator. Fittings and tubing for sampling and measuring head loss were inserted into the taps. The flocculator walls were reinforced by connecting U and L bars on both sides of the flocculator with allthread.

The overflow column, constructed from 1/2-inch thick acrylic, had dimensions of one-foot long by one-foot wide by eight-feet high. A permanent partition divided the column into two sections, each with a cross-sectional area of 0.5 ft^2. Six 1-1/4 inch valves at one-foot intervals were inserted into both sides of the column for use in controlling the water level in the flocculator. The overflow column had two purposes; it was always used to control the water level in the flocculator, and for some flocculation runs it was packed with media and operated in a manner similar to a sludge blanket clarifier.

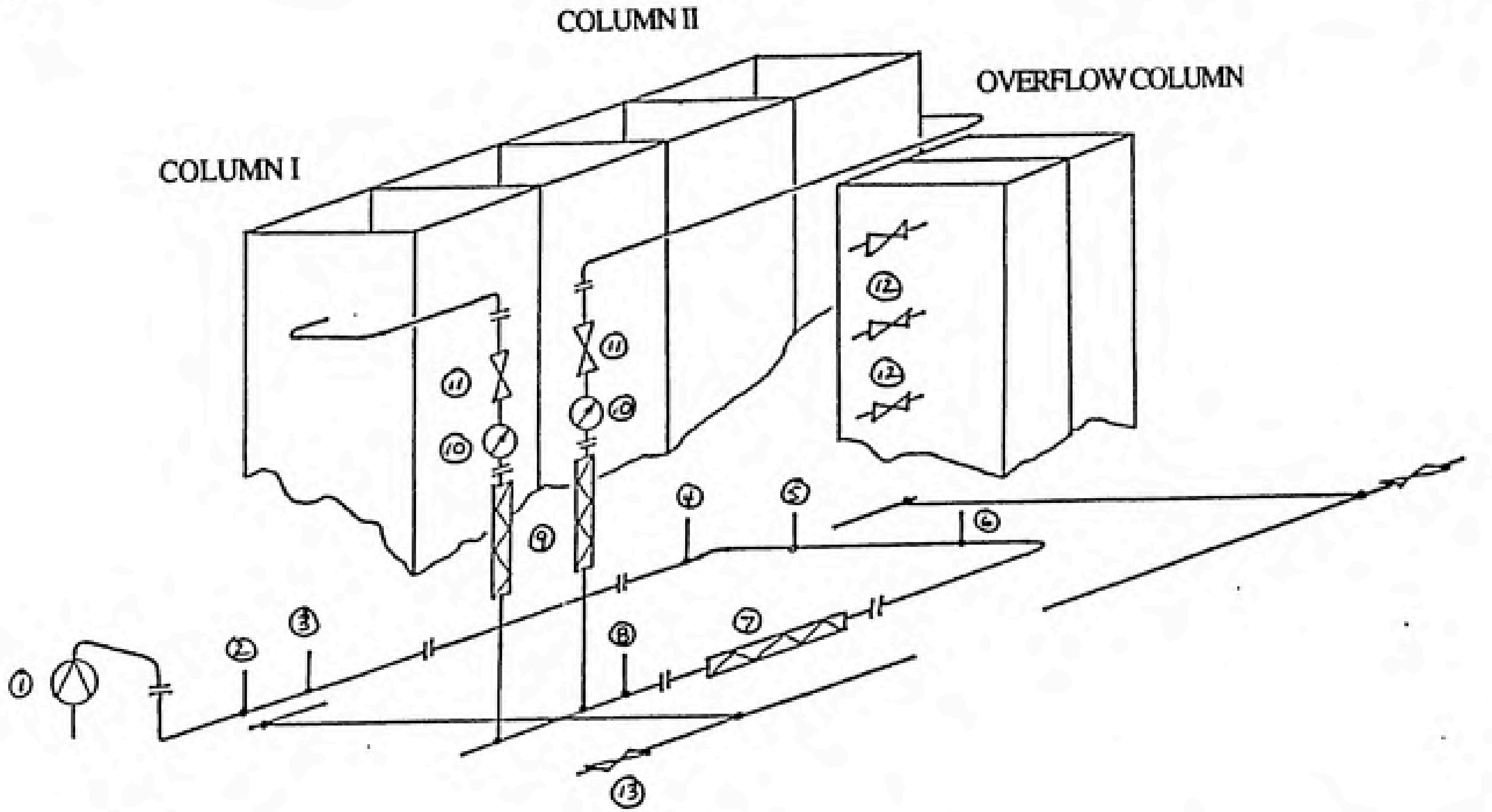


PHYSICAL ARRANGEMENT OF FLOCCULATOR
AND OVERFLOW COLUMN

FIGURE 3-1

Chapel Hill tap water was spiked with kaolinite clay to provide turbidity for testing. Water for flocculation runs was drawn from two 5000-gallon storage tanks. The tanks were filled with tap water from a water hose inside the laboratory and could be simultaneously filled and drawn. PVC piping connected the feed water storage tanks to the flocculator and the flocculator to the overflow column. A centrifugal pump (Little Giant Pump Co., Oklahoma City, OK Model No. TE7MDNC) driven by a 3/4-hp electric motor (Marathon Electric Co., Wausau, WI Model No. WQC56C34F290B) boosted inlet water from the storage tanks into the flocculator. Chemicals were mixed and stored in 11-gallon polyethylene tanks. Peristaltic pumps injected chemicals (kaolin slurry, coagulant, and polymer) into the flow line. A two-inch diameter by 17-inch long static mixer (Koflo Corp., Dundee, IL Model No. 2-40C-4-6-2) was inserted in the flow line downstream of all chemical injection points. To provide additional mixing, a 1-1/2 inch diameter by 17-inch long in-line mixer, constructed by bending sheet metal, was inserted into the pipe upstream of each flow meter. Figure 3-2 is a schematic of the flocculator and overflow column, the associated piping, and the chemical injection ports. The pilot plant was designed by Chris Schulz of Camp Dresser & McKee; the flocculator and overflow column were fabricated by Atlantic Plastics of Raleigh, NC.

To configure the flocculator in the straight bed mode (Figure 3-3A), three acrylic partitions, connected with allthread to maintain their separation, were inserted into the column. Twine was glued to the edges of the partitions to provide a better seal with the flocculator walls. Acrylic guides were glued to the bottom of the flocculator walls to hold the partitions in place. To insert the partitions, the flocculator had to be partially filled with water and the U and L



1. Water pump. Suction from water storage tanks.
2. Injection port for kaolin turbity source.
3. Injection port for coagulant.
4. Injection port for polymer.
5. Spare injection port.
6. Spare injection port.
7. In- line static mixer.
8. Sample port.
9. In-line static mixer.
10. Rotameter.
11. Flow control valve.
12. Level control valve.
13. Flow control valve to drain.

FIGURE 3-2: FLOCCULATOR AND OVERFLOW COLUMN PIPING SCHEMATIC

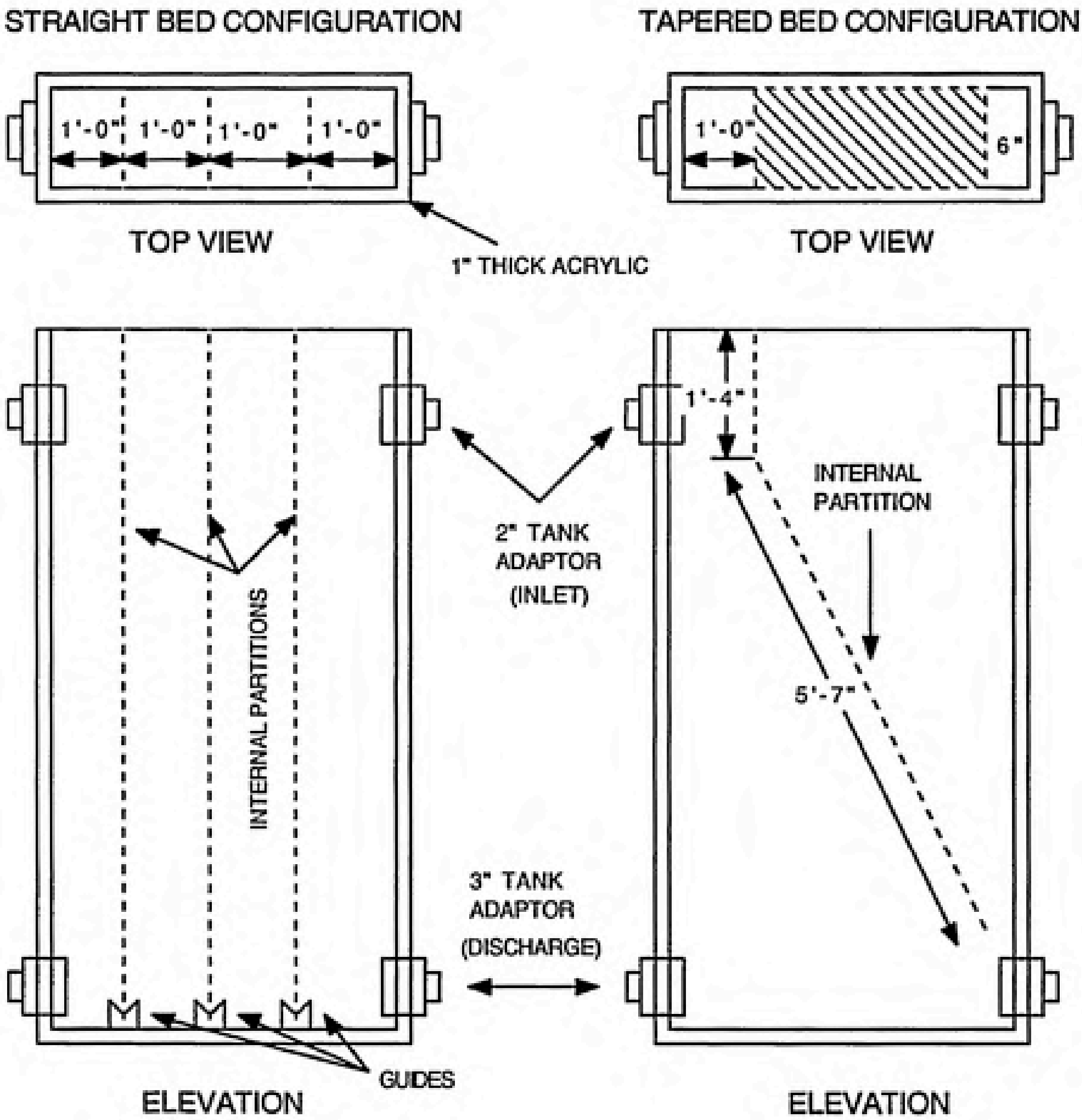


FIGURE 3-3A

FIGURE 3-3B

FLOCCULATION COLUMN DESIGN

bars removed to allow sufficient wall clearance. The partitions were inserted by lowering them from a catwalk above the flocculator.

To configure the flocculator in the tapered bed mode (Figure 3-3B), a single inclined partition at a 30° angle from the vertical was inserted into the column. The partition was constructed from a frame of aluminum into which was bolted an acrylic sheet. The lower end of the partition was held in place with a rope tied to the top of the flocculator. The upper end was bolted to reinforcing bars at the top of the flocculator. As with the straight bed partitions, inserting the tapered bed partition required that the flocculator be partially filled with water, the U and L bars removed, and the partition lowered from a catwalk.

In the tapered bed configuration, the flocculator was set up with one, rather than two, inclined walls. The reason for this was that the piping was not arranged so as to distribute influent water to the middle of the flocculator influent as would have been necessary had two incline walls been used for the taped bed. Had such a configuration been practical, two incline walls would have had the advantages of a more evenly distributed effluent flow and the potential use of both sides of the overflow column. Because water tends to take the shortest path through a bed of media, different flow characteristics and wall effects would have been established with two inclined walls.

B. Experimental Methods

This section presents the experimental methods used during the pilot plant study. The procedures described are jar tests, tracer studies, clean bed head loss tests, and flocculation runs. All jar tests, and all but the first three flocculation runs, were performed using a model water in which a controlled source of turbidity, kaolinite clay, was mixed with Chapel Hill tap water. Kaolin was chosen because of the ease with which it could be mixed with water and because it is a common source of turbidity in raw water.

Kaolin ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$) with a specific gravity of 2.63 was provided by Burgess Pigment Co. of Sandersville, GA. The other chemicals used during this study were alum, ferric chloride, polymer, and sodium bicarbonate. Alum ($Al_2(SO_4)_3 \cdot 14H_2O$), produced by General Chemical Co of Morristown, NJ., was provided in liquid form by the Orange Water and Sewer Authority (OWASA). Ferric chloride, also in liquid form, was provided by PVS Chemicals, Inc of Wyandotte, MI. The alum solution was 48.5% by weight and the ferric chloride solution was 38% by weight. The powdered cationic polymer, Betz 1160P, was produced by Betz Laboratories, Inc. of Trevose, PA and was provided by OWASA. The sodium bicarbonate was used for buffering the kaolin suspension; it was in powder form and was provided by the Arm & Hammer Division of Church and Dwight Co., Princeton, NJ.

1. Jar Tests

Jar tests were performed periodically before flocculation runs to optimize chemical dosages (both coagulant and polymer) under the conditions which would prevail during the run. The optimal chemical dosage was the lowest dosage which provided a supernatant turbidity of no more than 2 NTU after 20 minutes of settling. Conditions which were varied for jar tests were water temperature, rapid mix time, initial turbidity, types of coagulants, polymer, and pH. A Phipps & Bird (Model No. 300PM) jar test apparatus with six, two-liter square jars was used.

To reproduce the actual flocculation run conditions, water for the jar tests was collected from the water storage tanks in a five-gallon (18.9-l) plastic jug. To insure consistency and provide the desired turbidity, a previously-determined weight of kaolin was added to 12-liters of water. Sodium bicarbonate was added to the kaolin/water mixture to buffer the suspension. The target pH was 6.5 to 7.0 for the suspension after coagulant addition. The first jar tests performed used 164 mg/l of $NaHCO_3$ as a buffer. However, after measuring the pH of the suspensions after chemical addition, it was determined that lower dosages, 84 mg/l, and then 42 mg/l, of $NaHCO_3$ were sufficient. To insure consistency among the six samples, the water, kaolin, and sodium bicarbonate were mixed by shaking the five-gallon jug, and the mixture was poured into the test jars. Initial turbidity and pH from selected jars were measured before adding chemicals.

The desired quantity of liquid coagulant (and polymer if it was being tested) for each jar was measured by pipet into individual beakers. One jar, to be used as a control, received neither coagulant nor polymer. After turning on the mixer to its maximum speed of >100 RPM, coagulant (and polymer, if used) was added at the water surface, near the mixing shaft. For the jar tests where both coagulant and polymer were used, the two chemicals were either added at the same time, or polymer was added one minute after coagulant. The sequence for adding polymer depended on what was being investigated in a particular jar test. Following the desired rapid mix time, which could last from 45 seconds to two minutes depending on the purpose of the jar test, the water samples were subjected to tapered flocculation. The standard tapered flocculation consisted of mixing for five minutes each at 60, 30, and 15 RPM. After stopping the mixing, the water was allowed to settle quiescently for 5 and 20 minutes, at which times settled water turbidities were measured. Water samples were withdrawn through 1/4-inch tubing inserted into the sample port, four-inches below the water line and two-inches above the bottom of the jar. After 20 minutes of settling, pH was also measured.

2. Tracer Studies

Tracer studies were performed with both straight and tapered media bed configurations. There were three general objectives in running tracer studies: to estimate the mean residence time in the clean bed, to identify any short circuiting within or around the bed, and to insure that both beds behaved equivalently when the flocculator was in the straight bed configuration. All tracer studies were performed with methylene blue solutions. The methylene blue used was in powder form and was produced by Fisher Scientific Co. of Pittsburgh, PA. Samples of water leaving the media bed were taken periodically throughout the run, with frequent samples taken near the expected peak. The samples were spectrophotometrically analyzed by measuring the absorbance at 670 nm.

A calibration curve was constructed by measuring the absorbance of known concentrations of methylene blue (Figure 3-4). The methylene blue solutions used to construct the calibration curve were made by first preparing a stock solution of 6.30 mg/l and then making dilutions of 1:5 (1.26 mg/l), 1:10 (0.63 mg/l), and 1:50 (0.13 mg/l).

Both step and pulse tracer studies were performed. Step studies were performed in the earliest tracer studies. Later tracer studies used a pulse technique since it was easier to perform and provided results as accurate as the step studies.

The step tracer studies were run for four minutes at 5 and 10 GPM. The methylene blue stock solution, of concentration 2.5 g/l, was pumped at a constant rate into the influent water line. Thirty-ml samples were collected through tubing at the bottom of the media bed. The sample tubing was inserted into the 5/8-inch taps illustrated in Figure 3-1. The samples were analyzed for absorbance using a Hitachi Model U-2000 Double Beam spectrophotometer and a

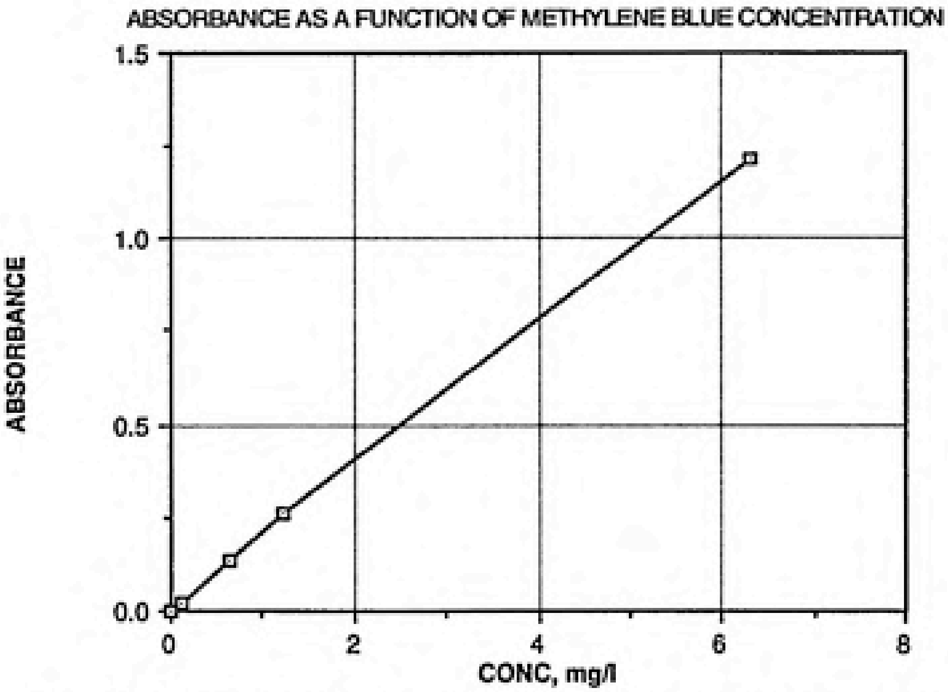


FIG. 3-4: METHYLENE BLUE CALIBRATION CURVE FOR TRACER STUDIES

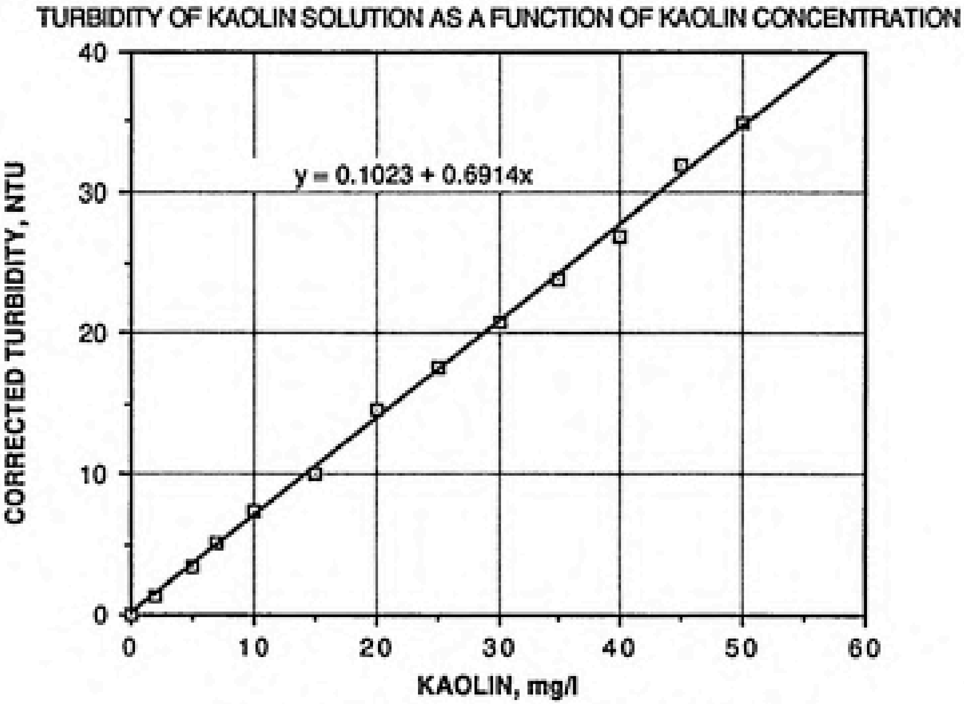


FIG. 3-5: KAOLIN CALIBRATION CURVE

one-cm cell. Using the calibration curve in Figure 3-4, the absorbance for each sample was converted into a concentration of methylene blue.

The relationship between the F curve, which is the system's response to a step input of tracer, and the mean residence time of the bed of media is:

$$F = \frac{C}{C_o} = 1 - \exp\left(\frac{-t}{\theta}\right) \tag{3-1}$$

where C = concentration of methylene blue at time t

C_o = inlet concentration of methylene blue

θ = mean residence time.[14]

Equation 3-1 rearranges to

$$-\ln\left(1 - \frac{C}{C_o}\right) = \frac{t}{\theta} \tag{3-2}$$

The mean residence time was then determined by plotting $-\ln\left(1 - \frac{C}{C_o}\right)$ versus t. The inverse of the slope of that line was the mean residence time of the bed.

For the pulse tracer studies, one-liter of 1.22 g/l methylene blue solution was released instantaneously on top of each media column being tested. Samples were taken in the same manner as the step tracer studies. Absorbance was converted to methylene blue concentration using the calibration curve in Figure 3-4. The formula used for calculating mean residence time was:

$$\theta = \frac{\sum_{i=0}^{\infty} t_i C_i \Delta t}{\sum_{i=0}^{\infty} C_i \Delta t} \tag{3-3}$$

where θ = mean residence time

C_i = concentration of methylene blue at time t_i

Δt = incremental time.[3]

3. Clean-Bed Head Loss and Flow Rate

Clean bed head loss was measured at various flow rates (5, 10, 15, 20, 25, and 30 GPM) when testing with the flocculator first began and when new media was introduced for testing. Head loss across the bed of media was determined by measuring the difference between two water levels: (1) the level of the water column in the tubing connected to the bottom of the bed (inserted into the 5/8-inch taps illustrated in Figure 3-1); and (2) the level of the influent water pooled above the bed. The purpose of this procedure was initially to confirm the hydraulic reproducibility of the two parallel straight columns. After this was confirmed, clean bed head losses were used to compare different media types and to compare calculated values of head loss against actual values. The Carmen-Kozeny Equation (Okun and Schulz, 1984) was used to calculate head loss:

$$h = \left(\frac{f}{\theta}\right)\left(\frac{1-\alpha}{\alpha^3}\right)\left(\frac{L}{d}\right)\left(\frac{v^2}{g}\right) \qquad (3\text{-}4)$$

$$\text{where } f = 150\left(\frac{1-\alpha}{R_N}\right) + 1.75 \qquad (3\text{-}5)$$

$$R_N = \frac{dvp}{\mu} \qquad (3\text{-}6)$$

h = head loss (m)

f = friction factor

θ= shape factor (0.8 for ceramic media and 1/2-inch cylindrical Norpak media and 1.0 for polypropylene media and 3/4-inch spherical Norpak media)

α = porosity (0.4 for ceramic and polypropylene media and 0.8 for Norpak media)

L = depth of media bed (m)

d = average diameter of media (m)

v = face velocity (m/s)

g = gravitational constant (9.81 m/s^2)

R_N = Reynolds number

ρ = density of water (kg/m^3)

μ = viscosity (kg/m-s).[1]

Flow rate was measured with series K72 rotameters manufactured by the King Instrument Co. of Huntington Beach, CA. (No. 10 in Figure 3-2) The rotameters were calibrated by timing the water flow through each rotameter into the empty flocculator. The volume of the empty flocculator was calculated for a given height of water. In this way the average flow rate could be calculated and compared to the rotameter reading. The rotameters were found to be accurate within 5% and repeatable. Flow rate was controlled with manual valves placed in the influent line to the flocculator, downstream of the rotameter and upstream of the flocculator.

4. **Flocculation Runs**

Flocculation runs were made to evaluate the performance of the flocculator under different operating conditions. A particular objective was to test the efficiency of the flocculation column in both the straight bed and tapered bed configurations. Also of interest were determining the best media type, media size, media depth, and the effect of layering different media sizes within the same bed of media. The various bed configurations were tested at different flow rates. Different chemicals, particularly coagulants, and chemical dosages were studied. Finally, the pilot plant was run for extended periods of time to study its performance at steady state. The media types tested are listed below in Table 3-1.

Chemicals to be used in a flocculation run were mixed with tap water to their desired strength in 11-gallon tanks and were pumped into the inlet water line using peristaltic pumps. The kaolin turbidity source and sodium bicarbonate buffer were mixed together in the same tank with water, using an impeller type mixer driven by an electric motor. A turbidity curve for kaolin (Figure 3-5) was used to determine the concentration of kaolin required for a desired turbidity. The curve was developed by measuring the turbidity of a known concentration of kaolin solution and dilutions of that solution. The kaolin/sodium bicarbonate slurry had to be mixed continually during a flocculation run to keep it in suspension.

TABLE 3-1: Types of Media Tested During Pilot Study

Media Manufacturer	Media Size	Media Type	Media Shape
3M Chemical Co., St Paul, MN	3/8 "	ceramic	spheroid
3M	1/2"	ceramic	spheroid
3M	3/4"	ceramic	spheroid
University Plastics, Inc., Ann Arbor, MI	1/4"	polypropylene	spheres
University Plastics	1/2"	polypropylene	spheres
NSW Corp., Roanoke, VA	1/2"	Norpak	open cylindrical
NSW Corp.	3/4"	Norpak	open spherical

Liquid alum or ferric chloride were mixed with water by manual stirring with a paddle. Polymer was mixed with warm water using an electric driven impeller type mixer to make it easier to get the polymer into solution. After the polymer was in solution the mixer was removed. The influent water, containing chemicals, flowed through two in-line static mixers (Nos. 7 and 9, Figure 3-2) before entering the flocculator.

Two important parameters were monitored throughout a flocculation run to evaluate pilot plant performance: (1) head loss across the entire bed of media and at various depths along the bed was measured in the manner outlined above for measuring clean bed head loss; and (2) nephelometric turbidity of the water into and out of the flocculator was measured with a Hach ratio turbidimeter (Model No. 18900). Both the instantaneous turbidity and 20-minute settled turbidity of the effluent water from the flocculator were monitored. After a two-liter sample of the flocculator effluent was taken, its turbidity was measured and then the sample was allowed to settle quiescently for 20 minutes when the turbidity was measured again. The pH of the water sample was measured using an Orion Research Inc. pH Meter (Model No. 399A). The pH meter was calibrated using the two-buffer standardization method at pH 4 and 7. The velocity gradient, G, was calculated for each data point using the head loss, flow rate, and porosity and volume of the bed. The equation used to calculate the velocity gradient was:

$$G = \sqrt{\frac{h\rho g Q}{\mu \alpha V}} \qquad (3\text{-}7)$$

where G = velocity gradient (s^{-1})

h = head loss (m)

ρ = density of water (kg/m^3)

g = gravitational constant (9.81 m/s^2)

Q = flow rate (m^3/s)

μ = viscosity (kg/m-s)

α = porosity (clean bed porosity of 0.4 for ceramic and polypropylene media and 0.8 for Norpak media)

V = volume of bed (m^3).[1]

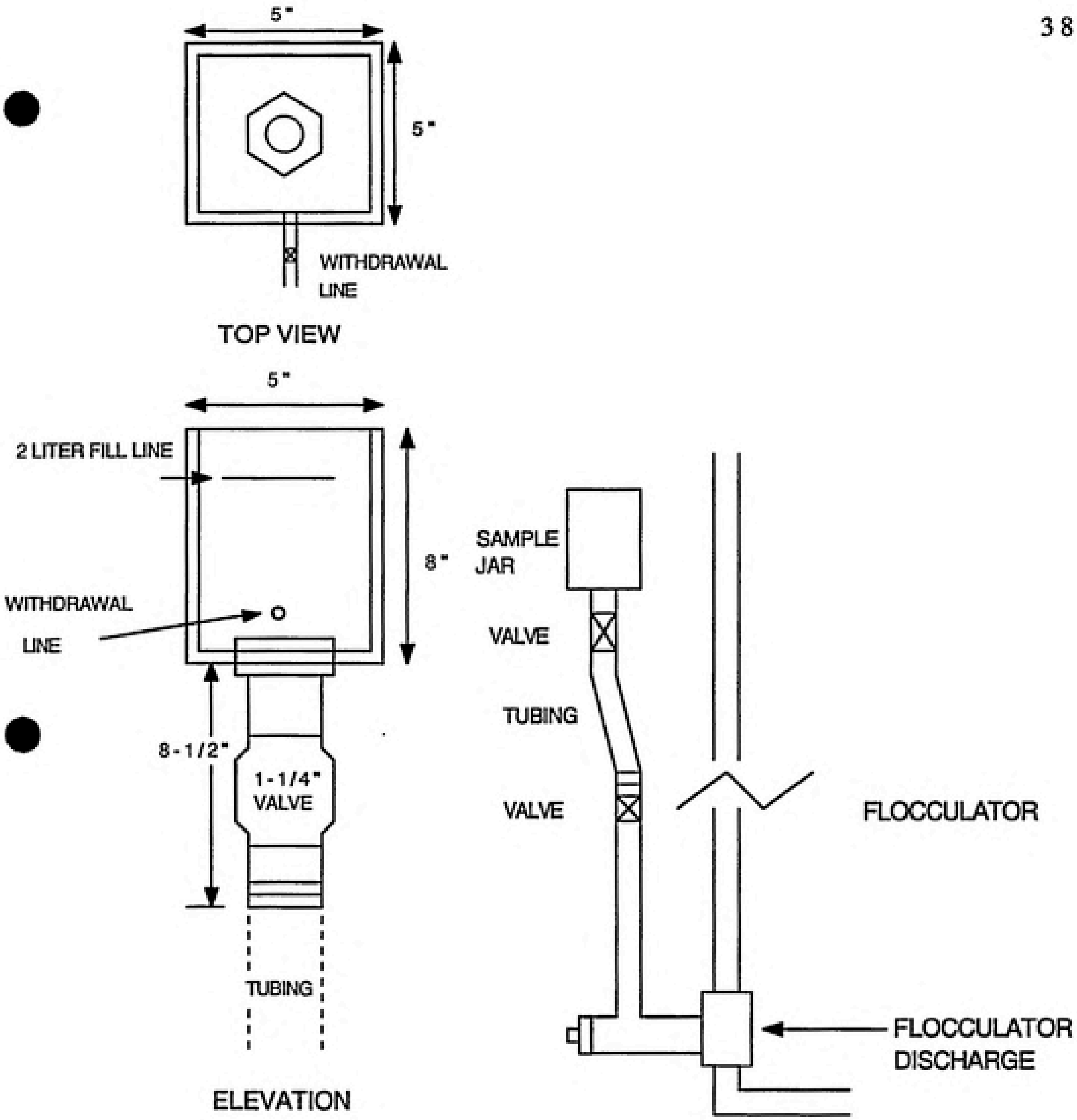
The frequency of data acquisition varied from hourly during the first few hours of a flocculation run to three times a day at the end of some runs.

Care was always taken when sampling the effluent from the flocculator. There were two main reasons for this: (1) the deposition of floc at the bottom of the flocculator; and (2) concerns with shearing floc during sampling. The deposition of floc was only a problem when the flocculator was being operated with the tapered bed. During this type of operation, the sample was taken through 1-1/4 inch tubing attached to the three-inch tank discharge adaptor (see Figure 3-3B). The deposits of floc in front of the tank adaptor were cleared sufficiently well by purging the sample tubing to insure that floc released by the bed during the sampling period, not deposited floc, were taken with the effluent sample. As described below, different sampling techniques were developed to mitigate floc breakup during sampling. These techniques included using larger sample tubing, elevating the sample jar, and taking a sample through the bottom of the sample jar rather than through the top of the jar.

Water samples from the flocculation column were taken from tubing at the bottom of the bed of media. Two different sample locations were used. From the initial flocculation run through run # 10, and also for run # 16, samples were taken from 5/8-inch tubing inserted into the taps in the sides of the flocculator (see Figure 3-1). This was considered a less-than-ideal sampling method because the small diameter of the tubing and the pressure head created undesirably high velocities while sampling and contributed to potential floc shearing. Before taking a sample, the tubing was purged by allowing water to flow into the drain. During runs #1 through #10, the sample was taken by allowing the water to flow slowly into the top of one of the jars used for jar tests. Efforts were made to reduce the sampling velocity by elevating the sampling jar. To further mitigate floc breakup, the sample jar was tilted to one side, allowing the water sample to flow down the side of the jar rather than free fall to the bottom of the jar. Still, it was felt that the speed of the water flowing into the top of the jar contributed further to the break-up of floc. Run #16 was sampled from the same 5/8-inch tubing, but was allowed to flow through the sample port in the side of the jar in an attempt to address the problem of floc breakup due to sampling into the top of the jar.

From runs # 11 through #15, samples were taken through a 1-1/4 inch tubing connected to the piping at the bottom of the flocculator (3" tank adaptor in Figure 3-3B). The tubing was first purged by allowing water to flow into the drain. Since some of the floc produced by the bed accumulate at the bottom of the flocculator, it was particularly important when sampling with the 1-1/4 inch tubing to purge the line until none of these previously-settled floc entered the tubing. The sample was then taken by allowing it to flow slowly into the top of a test jar. The combination of larger diameter tubing and elevating the sampling jar reduced the pressure head in the sample tubing and the corresponding exit velocity. However, it was believed that some floc breakup continued because the sample was still taken into the top of the jar.

The problem of floc breakup due to sampling into the top of the jar was addressed beginning with run #17, when samples were again taken through the 1-1/4 inch tubing at the bottom of the flocculator. Modifications were made to one of the test jars by tapping a 1-1/4 inch hole in the bottom of the jar and inserting pipe fittings. Pipe and a valve were made up to the fittings, and 1-1/4 inch tubing could be inserted over the pipe (Figure 3-6). When sampling, the tubing was purged in the same manner described above, but after purging, the tubing was attached to the connection at the bottom of the jar. With this new sampling procedure, sample water flowed through the tubing at a lower velocity and entered the sample jar from the bottom. After the sample was taken, both



SAMPLING MECHANISM

FIGURE 3-6

valves were closed and the tubing was disconnected from the piping on the jar. This technique was believed to provide a more representative sample with less floc shearing.

At the same time that effluent samples from the flocculator were taken, a sample of the coagulated water entering the flocculator was collected in a test jar. This sample of influent water, containing kaolin, sodium bicarbonate, coagulant, and polymer (if polymer was used in the particular run), had been mixed through one in-line static mixer (No. 7 in Figure 3-2). After measuring instantaneous turbidity, the sample was subjected to tapered mechanical flocculation of 5 minutes each at 60, 30, and 15 RPM on the jar test apparatus and then allowed to settled for 20 minutes, after which turbidity was measured. The purpose of flocculating coagulated water in this manner was to insure that the chemical dosages in the influent water to the flocculator were still proper and were sufficiently well-mixed.

The overflow column served two functions during this study. It was always used to control the water level in the flocculator by allowing the water to be discharged through one of the valves positioned at one-foot intervals along the column (No. 12 in Figure 3-2). For some of the runs, the overflow column was packed with media and used in a manner similar to a sludge blanket clarifier, trapping floc contained in the flocculator effluent and providing additional opportunities for further particle aggregation. Three-quarter inch spherical Norpak media was used to pack the overflow column. The large porosity (~0.8) of that media was considered necessary to provide opportunities for floc produced in the flocculator to aggregate into larger floc without causing excessive head loss. The loading rate to the overflow column was controlled by splitting the effluent water from the flocculator, allowing part to flow through the overflow column and the remainder to flow into the drain (No. 13 in Figure 3-2). Since no sample taps were provided in the overflow column, water samples were collected by dipping a beaker into the water at the top of the column. After instantaneous turbidity was measured, the sample was allowed to settle in the beaker for 20 minutes after which turbidity was again measured.

IV. RESULTS AND DISCUSSION

The results obtained during this pilot plant study are summarized and discussed below. Results from jar tests, tracer studies, clean bed head loss measurements, and flocculation runs are presented. Full details of all of these operations, presented in both spreadsheet and graphical form, are appended to this report.

A. Jar Tests

Jar tests were conducted to determine the effect of particular chemicals and their optimal dosages, the effect of temperature, and the effect of rapid mix on flocculation. Turbidity was measured after 5 and 20 minutes of quiescent settling; only the 20-minute settled turbidities are reported below. The specific objective of the jar tests was to determine the minimum dosage of coagulant (and coagulant aid, if necessary) which would provide a 20-minute settled water turbidity of ≤ 2 NTU. All of these jar tests used kaolin to provide turbidity to the water. Results of selected jar tests are summarized below.

Table 4-1 illustrates the effect of pH adjustment on coagulant requirements. An 18° C water with an initial turbidity of 20 NTU and alkalinity of 2.1×10^{-3} eq/l was used in this test. Table 4-1 shows that it was possible to meet the objective of settled water turbidity of ≤ 2 NTU at pH 7.5 without adjusting the pH. While a dosage of 10 mg/l of alum was sufficient at both pH 6.5 and 7.5, after 20 minutes of settling, the residual turbidity was less at the lower pH.

TABLE 4-1: Jar Tests of the Effect of pH on Alum Requirements
Initial conditions: 20 NTU turbidity; 2.1×10^{-3} eq/l alkalinity; 18° C

Alum dosage, mg/l:	5	10	15	20	25	30
Without pH Adjustment:						
20-min. settled turbidity, NTU	4.90	1.56	1.60	1.57	2.20	1.72
Final pH	7.50	7.60	7.55	7.50	7.45	7.40
With pH Adjusted to 6.5:						
20-min. settled turbidity, NTU	7.80	1.31	0.90	0.95	1.34	1.10
Final pH	6.35	6.40	6.15	6.15	6.10	6.10

TABLE 4-2: Jar Tests of the Effect of Using Only pH Adjustment
Initial conditions: 20 NTU turbidity; 2.1×10^{-3} eq/l alkalinity; 17° C

Initial pH	6.0	5.0	4.5	4.0	3.5	7.4
20-min. settled turbidity, NTU	16.0	14.0	17.0	16.0	15.0	17.0
Final pH	6.2	5.15	4.6	4.15	3.6	7.45

TABLE 4-3: Jar Tests of the Effect of Two Water Temperatures Using Alum
Initial conditions: 20 NTU turbidity; 1.6×10^{-3} eq/l alkalinity

Alum dosage, mg/l:	0	10	15	20	25	30
11.5° C:						
20-min. settled turbidity, NTU	19	15.8	8.2	4.9	5.5	5.1
20.0° C:						
20-min. settled turbidity, NTU	20	4.6	2.0	1.7	1.7	1.9

TABLE 4-4: Jar Tests of the Effect of a Range of Water Temperatures Using Alum
Initial conditions: 20 NTU turbidity; 1.1×10^{-3} eq/l alkalinity
Chemical dosages: 25 mg/l alum and 0.5 mg/l polymer

Temp, °C	6.1	7.4	8.6	9.4	11.0	12.7
20-min. settled turbidity, NTU	4.3	3.9	3.4	3.2	2.6	2.3

Jar tests were also performed using only pH adjustment and no coagulant to determine if this method of destabilizing the clay particles would be feasible, since the zero point of charge for kaolin is in the range of pH 3.3 to 4.6.[3] The results for a water of 20 NTU and an alkalinity of 2.1×10^{-3} eq/l are reported in Table 4-2. Little improvement in the turbidity of the water was observed with pH adjustment alone, indicating that at best, a slight degree of particle destabilization had occurred.

The effect of water temperature on flocculation was analyzed because, due to the duration of the pilot plant study, flocculation runs would be conducted over a wide range of temperatures. Two jar tests using 20 NTU water were run to optimize coagulant dosage. One jar test used only tank water at 11.5° C and the other jar test used tank water diluted with hot tap water from the laboratory for a composite temperature of 20° C. The pH of both waters was 6.8 to 7.1; alkalinity was 1.6×10^{-3} eq/l. The results of these two jar tests are summarized in Table 4-3. Residual turbidities were appreciably lower at 20° C than at 11.5° C. The lowest 20-minute settled water turbidity achieved at 11.5° C was 4.9 NTU.

A third jar test investigating temperature effects was run over a range of water temperatures from 6.1 to 12.7° C. The initial water turbidity was 20 NTU and alkalinity was 1.1×10^{-3} eq/l; all jars were dosed with 25 mg/l alum and 0.5 mg/l polymer. Settled water pH was 6.8. The results are presented in Table 4-4, further illustrating the effect of temperature on flocculation and verifying that flocculation effectiveness deteriorates as water temperature decreases.

TABLE 4-5: Jar Tests of the Effect of Water Temperature Using $FeCl_3$
Initial turbidity of 20 NTU

$FeCl_3$ dosage, mg/l:	10	11	12	13	14	15
11.6° C (pH 6.6, Alk $1.6x10^{-3}$ eq/l):						
20-min. settled turbidity, NTU	1.9	1.4	0.8	0.9	0.7	0.7
13.0° C (pH 6.6, Alk $1.1x10^{-3}$ eq/l):						
20-min. settled turbidity, NTU	-	0.6	0.5	0.3	0.4	0.6
17.2° C (pH 6.7, Alk $1.1x10^{-3}$ eq/l):						
20-min. settled turbidity, NTU	0.6	0.4	0.4	0.3	0.4	0.5
23.5° C (pH 6.9, Alk $1.1x10^{-3}$ eq/l):						
$FeCl_3$ dosage, mg/l	10	0	2	4	6	8
20-min. settled turbidity, NTU	2.0	20	19	18	18	7.1

TABLE 4-6: Jar Tests of the Effect of Polymer Using $FeCl_3$
Initial conditions: 20 NTU turbidity; 1.1x10-3 eq/l alkalinity, 17° C

20 min settled turbidity, NTU	$FeCl_3$ dosage, mg/l		
Polymer dosage, mg/l	12	13	14
0.0	0.6	0.7	0.8
0.1	0.6	0.7	0.6
0.3	0.3	0.4	0.4
0.5	0.5	0.4	0.4

TABLE 4-7: Jar Tests of the Effect of Rapid Mix Using Polymer and Alum
Initial conditions: 20 NTU turbidity; 1.1x10-3 eq/l alkalinity; 11° C
Coagulant dosage: 25 mg/l

Jar number	1	2	3	4	5	6
Polymer dosage, mg/l	0.3	0.5	0.3	0.5	0.3	0.5
20-min. settled turbidity, NTU	1.6	1.4	1.2	1.2	1.2	1.0

Jar tests were also conducted at different temperatures using ferric chloride as the coagulant. The results of these tests are summarized in Table 4-5. These jar tests all used a water with an initial turbidity of 20 NTU. For jar tests conducted at 11.6° C, 13.0° C, and 17.2° C using the same coagulant dosage, residual turbidity decreased with increasing water temperature. The jar test conducted at 23.5° C is not directly comparable since lower dosages were tested.

As detailed in Table 4-6, the effect of polymer on flocculation was also tested with ferric chloride as the coagulant, using a 17° C water with initial turbidity of 20 NTU and an alkalinity of 1.1×10^{-3} eq/l. Residual pH was 6.6 to 6.7. These results indicate that the use of polymer with ferric chloride improved settled water turbidity only marginally.

Table 4-7 illustrates different rapid mix regimes which were tested using alum and polymer. Initial turbidity was 20 NTU; alkalinity was 1.1×10^{-3} eq/l; water temperature was 11° C; and final pH was 6.6. All six jars were dosed with 25 mg/l of alum, and polymer dosages were 0.3 and 0.5 mg/l. Jars 1 and 2 were rapid mixed for one minute after concurrent addition of alum and polymer; Jars 3 and 4 were rapid mixed for one minute after addition of alum, then polymer was added and rapid mix proceeded for an additional minute; Jars 5 and 6 were rapid mixed for two minutes after concurrent addition of alum and polymer. While all six combinations of chemicals and rapid mix produced 20 minute settled turbidities of ≤ 2 NTU, the best result was with 0.5 mg/l polymer and two minutes of total rapid mix. This illustrated the importance of adequately mixing chemicals before the raw water was subjected to flocculation.

B. Tracer Studies

Tracer studies were conducted using both the straight bed and the tapered bed in order to compare theoretical and mean residence times, identify any short-circuiting within the bed of media, and identify any flow around the partitions in the flocculator.

The first set of tracer studies used a step input of methylene blue solution and was conducted with 2-1/2 feet of 1/2-inch polypropylene media in each column in the straight bed configuration. The purpose of this study was to establish that the two parallel columns performed similarly. Based on the curves in Figure 4-1 and 4-2 and the calculated mean residence times of the tracer studies, the performance of the two columns was found to be similar at flow rates of 5 GPM and 10 GPM, the two rates tested. At 5 GPM, the theoretical residence time of each of the columns was 134 seconds and the mean residence times of the two columns were calculated from tracer data to be 146 and 136 seconds; at 10 GPM, the theoretical residence time was 67 seconds and the mean residence times of the columns were calculated to be 89 and 92 seconds. Calculations of mean residence time used a porosity of 0.40. The larger difference between theoretical and mean residence time at 10 GPM, as compared to 5 GPM, was probably due to the longer residence times in the inlet and outlet of the flocculator when compared to the residence time in the bed. In this and all other tracer studies, only minor amounts of tracer were observed to flow around the partitions. Flow around partitions was subsequently corrected by tightening or changing the location of the U and L bars which reinforced the flocculator walls.

Using pulse inputs of methylene blue solution, different sizes of the same type of media were compared. These tests were performed when the beds of media were clean. Depths of the beds were five to six feet, since these were the approximate bed depths to be used in the flocculation runs. Table 4-8 lists the theoretical and mean residence times of the four different media tested. Agreement was good between theoretical and mean residence times. Differences

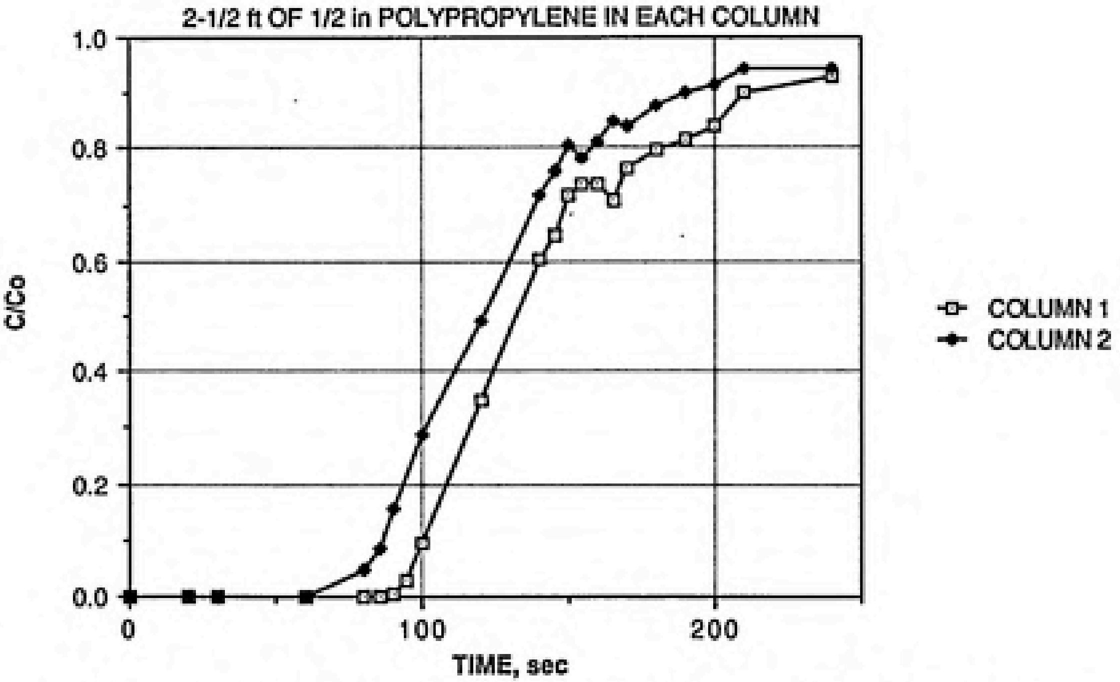


FIG 4-1: STEP TRACER STUDY, PARALLEL COLUMNS, 5 GPM

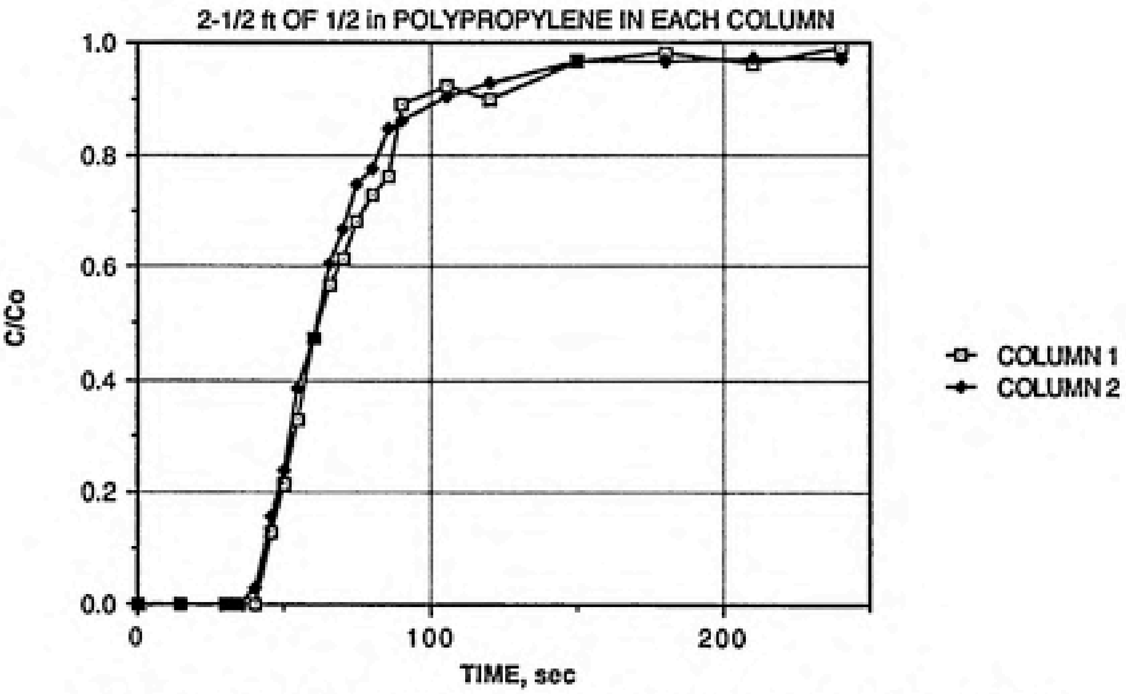


FIG. 4-2: STEP TRACER STUDY, PARALLEL COLUMNS,10 GPM

between the two can be explained by slight variations in porosity from the estimated values and additional residence time both above and below the bed.

TABLE 4-8: Results of Pulse-Type Tracer Studies
Porosity of 0.4 for Ceramic and 0.8 for Norpak

Media type	Media size	Bed depth	Flow Rate	Residence Time, sec	
			GPM	Theoretical	Mean
Ceramic	3/8"	5'	10	119	137
Ceramic	1/2"	5' 6"	10	105	116
Norpak	1/2"	5' 6"	10	229	211
Norpak	3/4"	5' 11-1/2"	10	234	226

One set of pulse tracer studies was performed on a tapered bed of stratified ceramic media. The test was performed first when the bed was still clean and again after it had been in operation for 110 hours. The purpose of the second test was to estimate the porosity of the bed after ripening. Both tracer studies were performed at 15 GPM. The mean residence time of the clean bed (α=0.40)was found to be 167 seconds and of the ripened bed was 90 seconds (See Figures 4-3 and 4-4). The porosity of the clean ceramic media had previously been estimated at 0.40 by measuring the volume of water required to fill a known volume which had media in it. The calculated porosity of the ripened bed was therefore ($\frac{90}{167}$*0.4=) 0.22.

C. Clean-Bed Head Loss

Head loss measurements at various flow rates were made on clean beds of media in order to compare different media types and sizes, to compare measured head loss with calculated values, and to determine which media could provide the

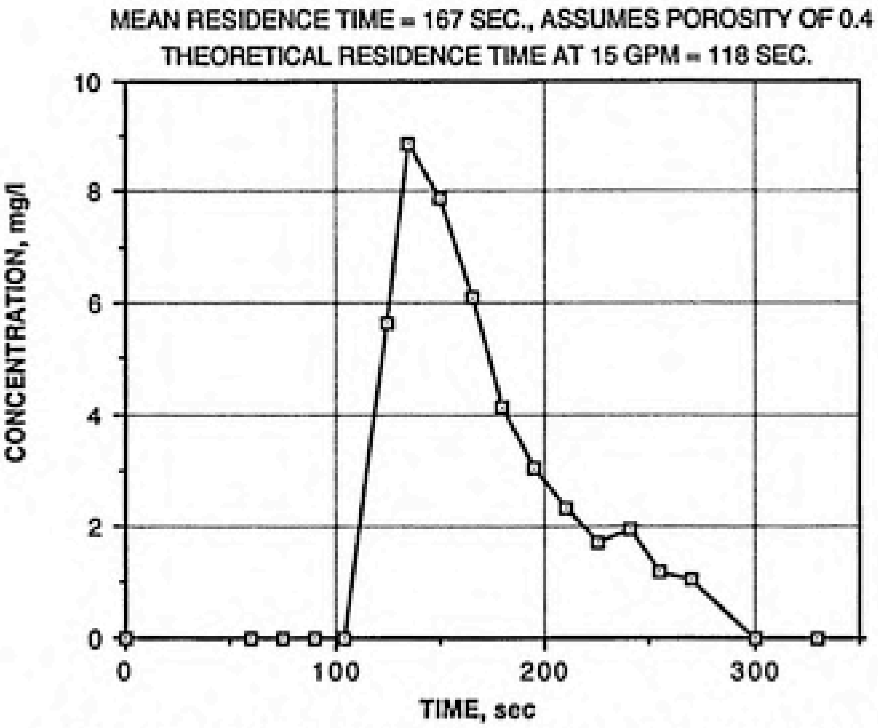


FIG. 4-3: PULSE TRACER STUDY; CLEAN, TAPERED MEDIA BED

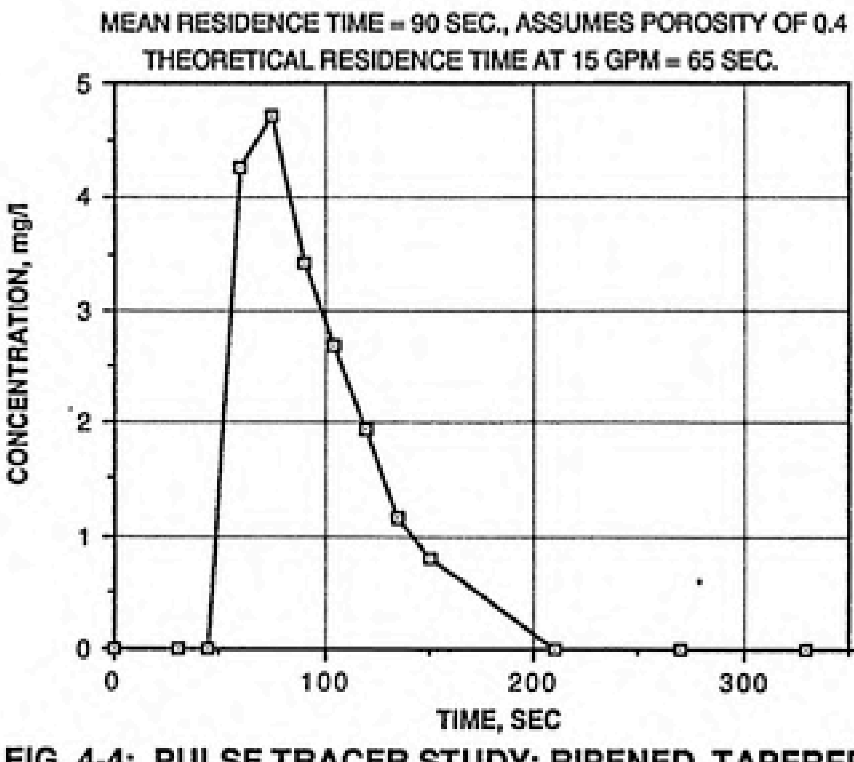


FIG. 4-4: PULSE TRACER STUDY; RIPENED, TAPERED MEDIA BED

head losses necessary to develop effective velocity gradients. The first studies were performed with both straight bed columns filled with 2-1/2 feet of 1/2-inch polypropylene media. Head loss was measured at various flow rates. However, due to the short bed depth, only 4 mm of head loss was achieved at the highest flow tested, 30 GPM.

Longer bed depths were tested to determine the clean bed head loss for all media which would be used in flocculation runs. The results, reported in mm of head loss/ft of media, to normalize for slight variances in bed depth, are presented in Table 4-9.

TABLE 4-9: Comparison of Head Loss for Different Media Types and Sizes Velocity Gradient, G, was calculated using the measured head loss.

Media type	Media Size	Bed depth	Flow Rate GPM	Measured Head Loss, mm/ft	Calculated Head Loss, mm/ft	Calculated G sec^{-1}
Polypropylene	1/4"	4' 6"	15	14.3	16.6	97
Polypropylene	1/2"	4' 6"	15	6.4	6.2	65
Ceramic	3/8"	5' 11-1/2"	25	25.0	26.9	165
Ceramic	1/2"	5' 6"	25	21.1	18.8	152
Norpak	1/2"	5' 6-1/2"	30	1.9	0.9	36
Norpak	3/4"	5' 11-1/2"	30	1.0	0.5	26

The calculated velocity gradients for Norpak were considered too low to allow that type of media to be considered acceptable for flocculation runs. A media which could generate a velocity gradient in the range of 50 to 150 s^{-1} was desired. However, for both the ceramic and polypropylene media, head loss was sufficient to establish the desired velocity gradients within the bed. As expected, the columns with smaller media had higher head losses at all flow rates. Calculated head losses were similar to the measured values for both the ceramic and polypropylene media, with the greatest difference being 16% for 1/4-inch polypropylene media. Variations between measured and calculated head loss can be attributed to wall effects and slight variations in the measured flow rate. Due to the small head loss developed by the Norpak media and the irregular shape of the media, the difference between calculated and actual head loss was ≥ 50% for both sizes of that type of media.

D. Flocculation Runs

Ten flocculation runs with the straight bed configuration and fourteen flocculator runs with the tapered bed configuration were performed during this study. The objective of these runs was to produce an effluent water with a maximum turbidity of 2 NTU after 20 minutes of settling. Complete data from flocculation runs can be found in the appendix.

Table 4-10 and Figures 4-5 through 4-8 are examples of the flocculation data collected. This flocculation run is included as an illustration of how data were typically recorded and graphed. The heading of Table 4-10 includes the run number and the date on which the run began. The heading also includes basic information about the run conditions such as the target influent turbidity, which coagulant was used, coagulant dosage, the dosage of polymer, the $NaHCO_3$ added, and the pH and temperature of the influent water. The types of media used during this particular run are listed as five feet of 3/8-inch ceramic media (3M) in the downflow configuration and 4.2 feet of 3/4-inch Norpak media (NP) in the upflow configuration. Downflow indicates that the media was in the flocculator and upflow indicates that the media was in the overflow column. The following is an explanation of the columns listed in Table 4-10:

TABLE 4-10: Example Flocculation Run Data

COAGULATION RUN # 9 02/07/91

FEED WATER CHARACTERISTICS:

Turbidity:	20	NTU
Coagulan: FeCl3	11	mg/l
Polymer:	0	mg/l
Alkalinity: NaHCO3	84	mg/l
Raw Water pH with FeCl3	6.7-7.1	
Temperature:	10.4-10.6	C

Media:	3/8 " 3M	Bed Depth 5.0	ft	Downflow
	3/4 " NP	Bed Depth 4.2	ft	Upflow

SAMPLE #	TIME h	HEAD LOSS mm	G - VALUE 1/s	Flocculator TURBIDITY,NTU EFFLUENT	SETTLED	Overflow Column TURBIDITY,NTU EFFLUENT	SETTLED	SETTLED INFLUENT TURB.
0	0.0	221	101.2	23.0				
1	1.0	237	104.8	8.0	6.5	11.0	10.0	3.3
2	2.0	245	106.6	11.0	5.6	4.7	3.3	1.7
3	3.0	253	108.3	12.0		5.0	3.4	0.9
4	7.5	264	110.6	14.0	8.3	9.0	7.7	1.5
5	8.3	270	111.9	23.0		5.4		2.3
6	9.0	271	112.1	15.0	7.5	5.6	5.2	3.8
7	11.0	271	112.1	14.0	8.3	5.3	4.7	3.0
8	12.0	274	112.7	15.0	8.3	5.2	4.7	2.3
9	12.5	272	112.3	15.0	6.0	4.7	4.2	1.7
10	15.0	274	112.7	14.0	6.5	4.2	3.7	1.6
11	17.0	280	113.9	13.0	7.5	5.0	4.4	1.7
12	19.0	285	114.9	14.0	7.7	6.8	6.6	0.9
13	21.0	284	114.7	16.5	8.4	9.3	8.5	0.9
14	23.0	293	116.5	13.0	7.0	6.9	5.4	1.1
15	25.5	297	117.3	13.0	5.8	7.5	6.8	1.2
16	27.0	293	116.5	12.0	6.2	10.0	9.0	1.2

Procedures / Remarks

* Norpak was slightly covered with floc after 15 min and accumulated floc mass steadily. Only small particles left the NP-bed (visual).
* After app. 15 hrs of run time NP Bed was loaded and released big floc. These floc were at the size of app. 5 to 6 mm and obviously torn apart from the bed. Small particles still remained in the effluent.
* Sampling of overflow samples is questionable because of heavy floc shearing
* Steady state porosity of NP in the overflow column was estimated to be between 0.5 and
* Residence time in the NP bed was app. 123 s

1. SAMPLE #

2. TIME is the elapsed time of the run at which a particular sample was taken. In Table 4-10, time is reported in hours, but other flocculation run spreadsheets in the Appendix report time in minutes.

3. HEAD LOSS is the measured head loss across the bed of media reported in millimeters (mm). If a stratified bed or a tapered bed was used, head loss is reported at different depths of media in addition to being reported across the entire bed.

4. G-VALUE is the calculated velocity gradient reported in sec^{-1}. If a stratified or tapered bed was used, G is reported for different depths of the bed.

5. FLOCCULATOR indicates that the two entries, EFFLUENT and SETTLED, are for the flocculation column. "Effluent" refers to the instantaneous turbidity of the water leaving the flocculator, and "Settled" refers the turbidity after 20 minutes of settling. Both values are reported in NTU.

6. OVERFLOW indicates that the entries, EFFLUENT and SETTLED, are for the overflow column. "Effluent" refers to the instantaneous turbidity of the water leaving the packed overflow column, and "Settled" refers to the 20-minute settled turbidity of that water. Both are reported in NTU.

7. SETTLED INFLUENT TURB. refers to the influent water to the flocculator. The sample was taken after all chemicals had been added and the water had flowed through one in-line static mixer. The sample was subjected to tapered mechanical flocculation of 5 minutes each of 60, 30, and 15 RPM on the jar test apparatus before being allowed to settle quiescently for 20 minutes, after which it was sampled.

8. PROCEDURES/REMARKS record notable occurrences during the flocculation run.

Data presented in Table 4-10 are plotted in Figures 4-5 through 4-8. Figure 4-5 is a plot of the increase in head loss as the run progressed and shows head loss building to approximately 300 mm after 25 hours of run time. Because the initial head loss was 220 mm, the bed contained floc entrapped from a previous flocculation run. Figure 4-6 is a plot of calculated velocity gradients corresponding to the head losses in Figure 4-5 and shows that the velocity gradient was in the range of 100 to 120 sec^{-1} throughout this run. Figure 4-7 is a composite plot showing the turbidity of the influent water to the flocculator, the instantaneous turbidity of the effluent water from the flocculator, and the turbidity of the effluent water from the flocculator after 20 minutes of settling, all versus time. As can be seen in Figure 4-7, 20 minutes of settling reduced the effluent turbidity from an average of approximately 13 NTU to an average of six to seven NTU. The settled turbidity was never below five NTU for this run. Figure 4-8 is a plot of the instantaneous and settled turbidities of the effluent water from the packed overflow column versus time. This figure illustrates the advantage of allowing the previously flocculated water to flow through the packed overflow column; settled turbidities as low as 3 to 4 NTU were achieved for this run. The wide variation in turbidity exhibited in Figure 4-8 was the result of the bed ripening with floc early in the run and of the sampling technique of dipping a beaker into the water at the top of the column.

1. Straight Bed Configuration

The initial flocculation runs were conducted to test the similarity of performance of the two straight columns and to compare different media types and sizes. One flocculation run in this series was designed to compare 3/8-inch ceramic (3M) media against 1/4-inch polypropylene (PP) media. This run was performed using the two straight flocculation columns run in parallel. All other comparisons of flocculation performance reported below are the result of

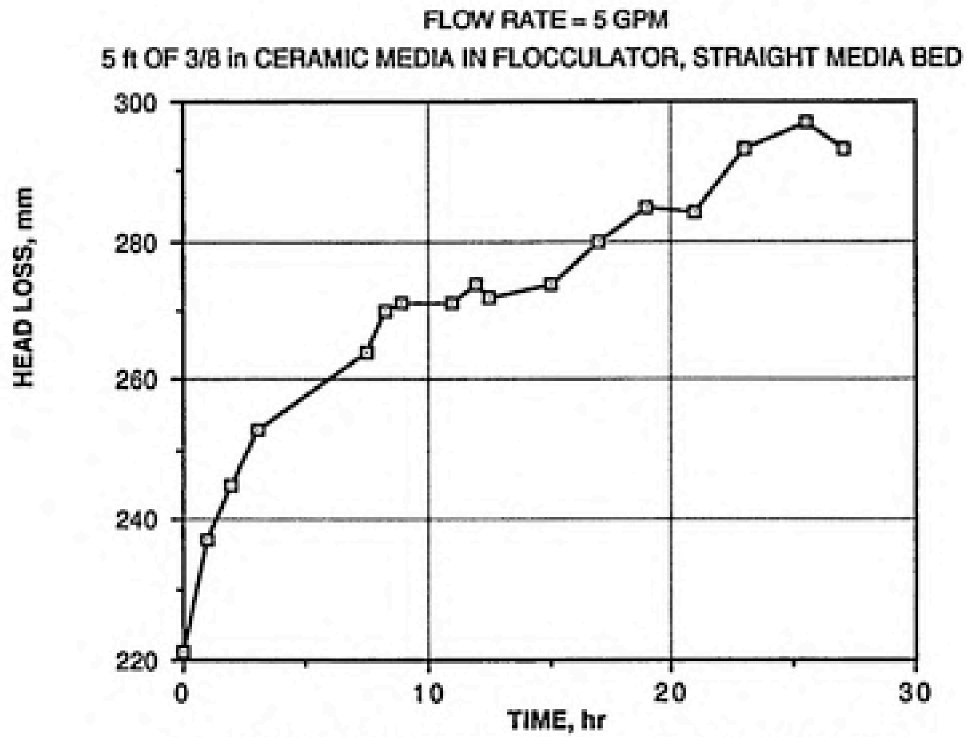


FIG. 4-5: EXAMPLE HEAD LOSS BUILD-UP

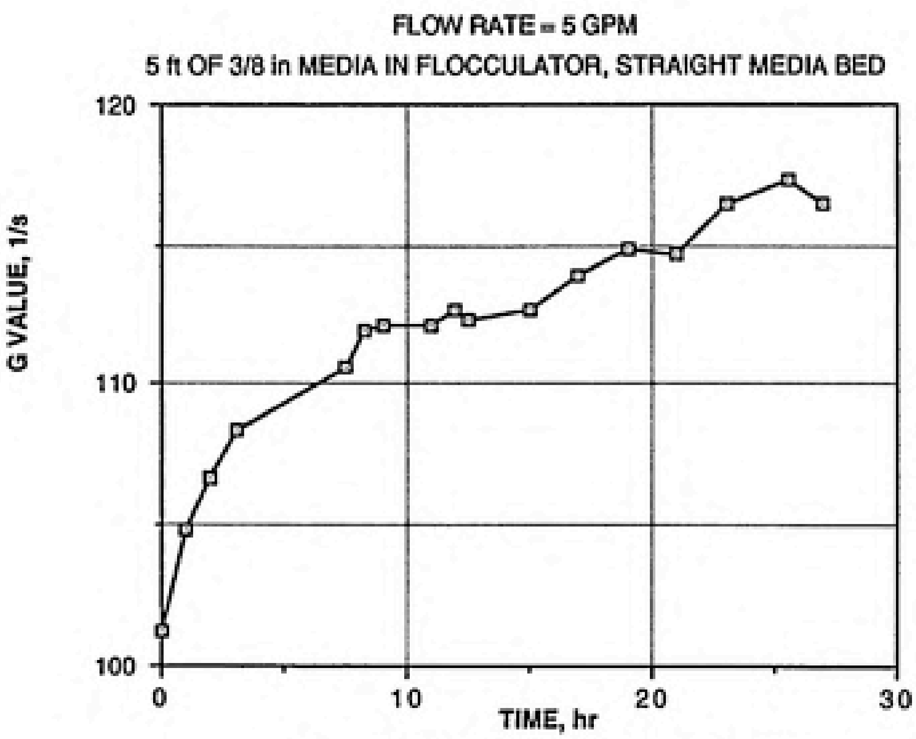


FIG. 4-6: EXAMPLE G VALUE v TIME

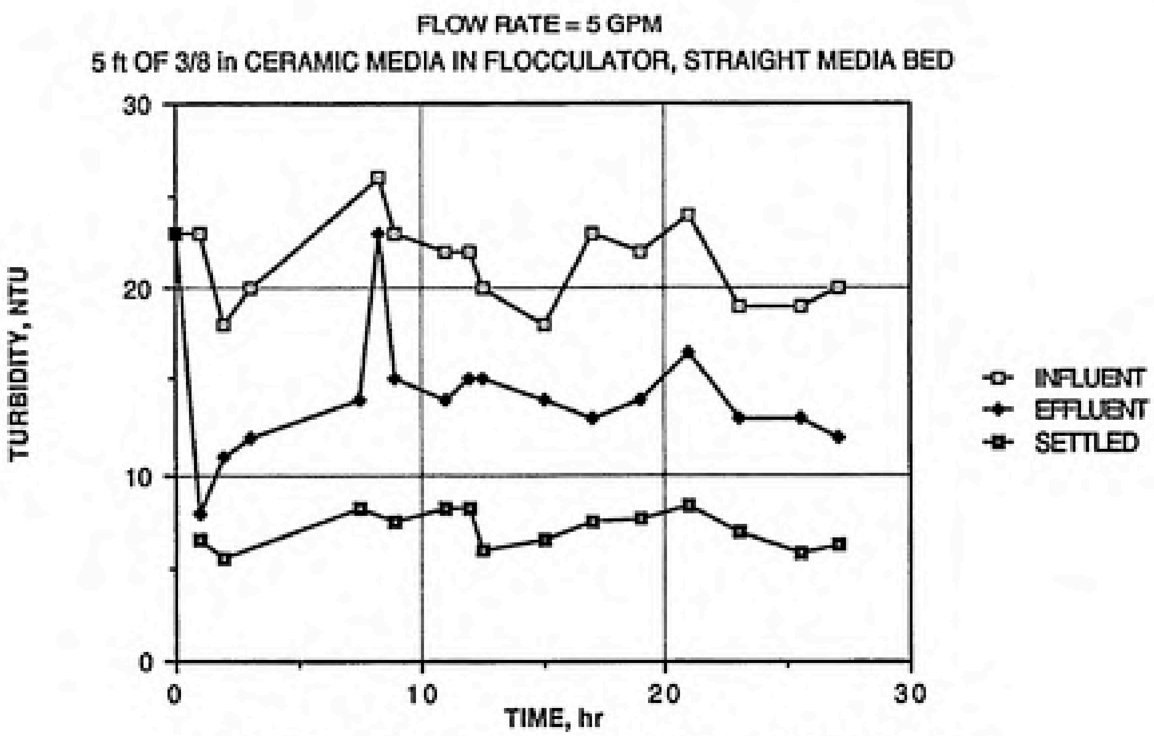


FIG. 4-7: EXAMPLE FLOCCULATOR TURBIDITY

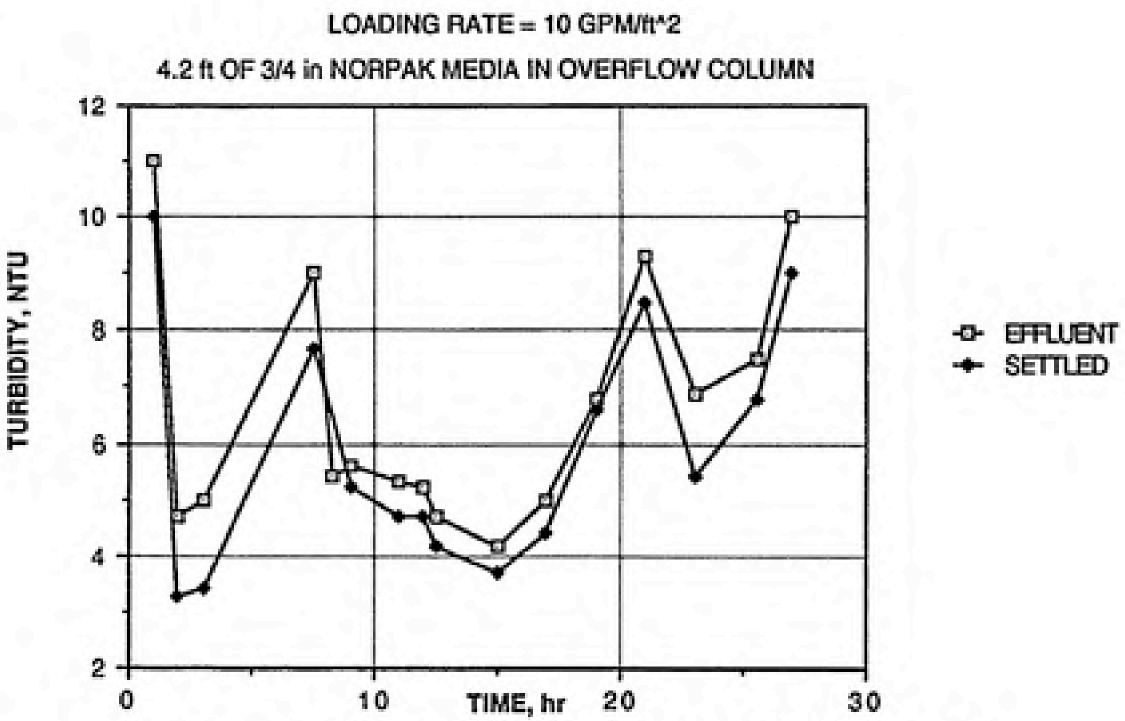


FIG. 4-8: EXAMPLE OVERFLOW COLUMN TURBIDITY

sequential runs. This flocculation run was performed at 10 GPM, corresponding to a loading rate of 10 GPM/ft^2, with both 200 NTU and 20 NTU influent water to the flocculator. Water temperature was 10° C. Alum was used as the coagulant at a dosage of 25 mg/l; polymer dosages of 0.1 to 0.2 mg/l were also used. Figure 4-9 plots the effluent and settled turbidities from both types of media; the influent turbidity was initially 200 NTU, but was lowered to 20 NTU for the latter portion of the run. The instantaneous and settled effluent turbidities for both types of media were similar. Figure 4-10 illustrates that head loss build-up was similar for both types of media. There was no apparent advantage with either type of media, and neither media achieved a settled water turbidity below 10.0 NTU. Since there was no advantage in using polypropylene media and ceramic media is less expensive than polypropylene media, the decision was made to conduct the remainder of the pilot plant work using ceramic media.

The flocculation runs summarized in Table 4-11 and plotted in Figures 4-11 and 4-12 were performed using a ripened five-foot bed of 3/8-inch ceramic media. These runs, which were conducted with 10° C water, were designed to study the performance of the bed of ceramic media at various flow rates. The lowest flow rate of 5 GPM (5 GPM/ft^2) provided the best results, possibly due to the longer retention time at this flow rate. The retention times in the bed were approximately three minutes at 5 GPM, two minutes at 10 GPM, and one minute at 15 GPM. The performance as measured by both instantaneous and settled turbidity appeared to be better at 15 GPM (15 GPM/ft^2) than at 10 GPM (10 GPM/ft^2). This may be attributable to the fact that 10 GPM was the first flow rate tested, when the bed had not ripened sufficiently with captured floc, and 15 GPM was the last flow rate tested, when the bed was well-ripened.

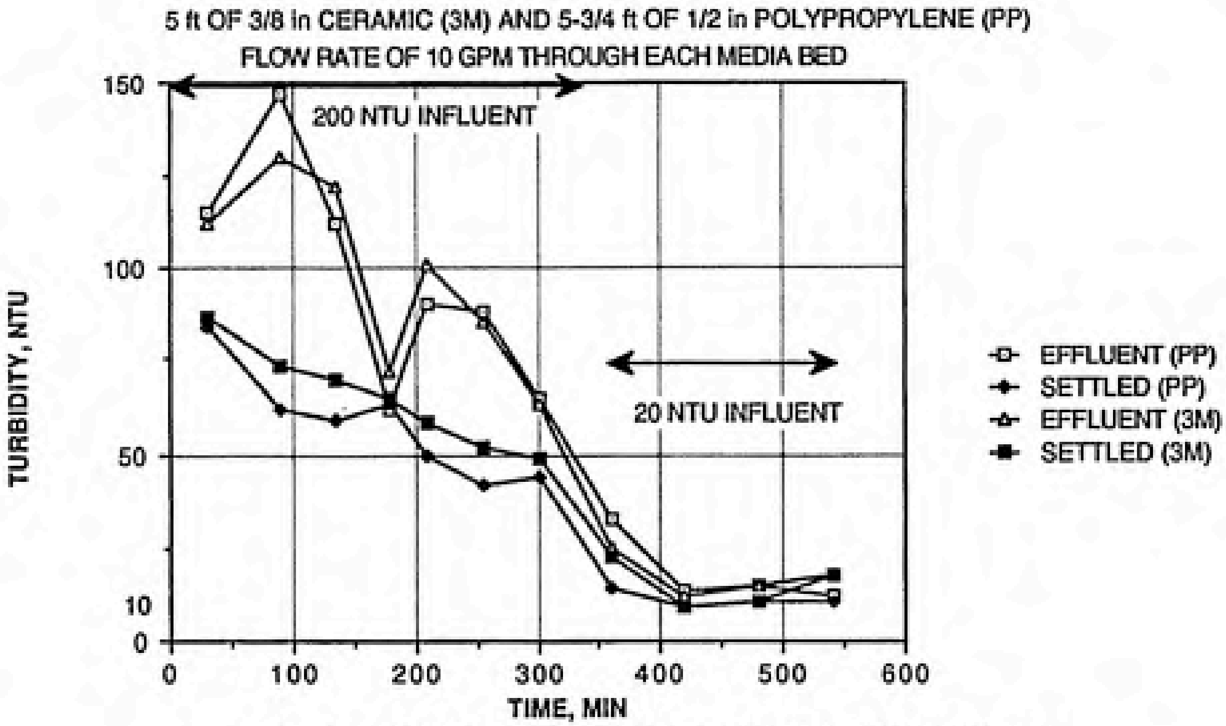


FIG. 4-9: COMPARISON OF FLOCCULATION WITH POLYPROPYLENE AND CERAMIC MEDIA

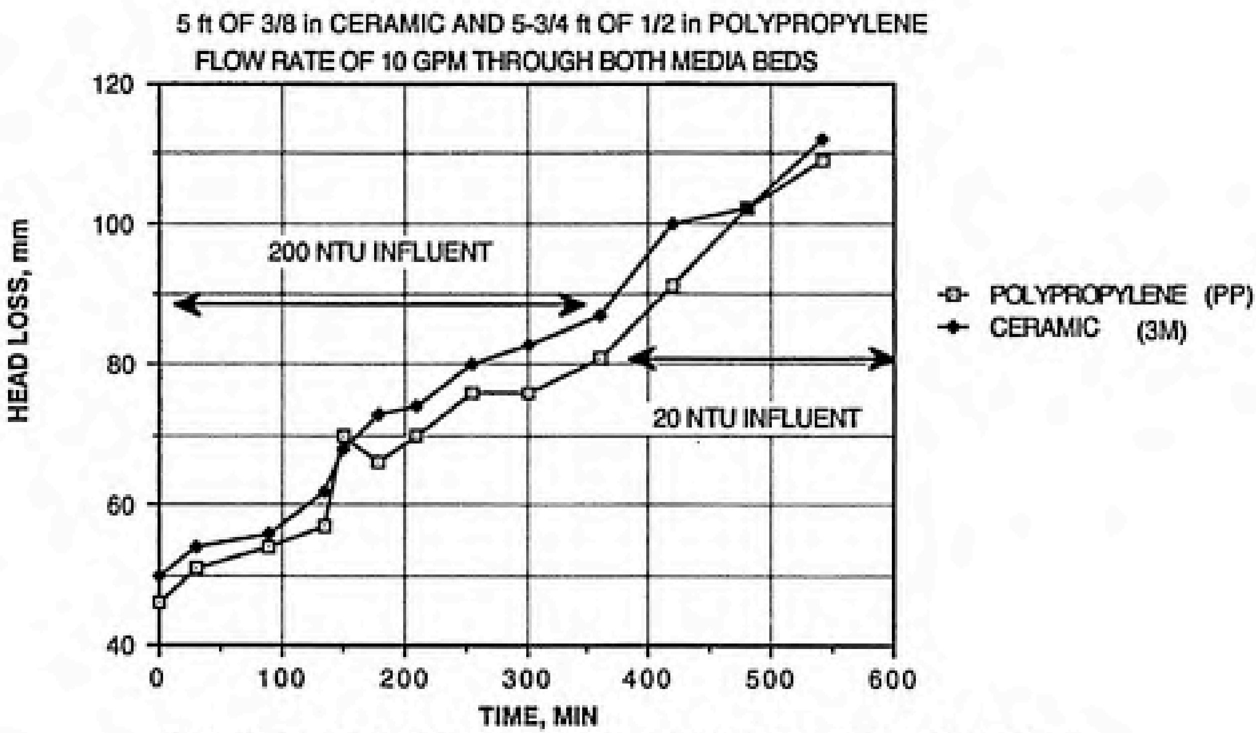


FIG. 4-10: COMPARISON OF HEAD LOSS BUILD-UP FOR POLYPROPYLENE AND CERAMIC MEDIA

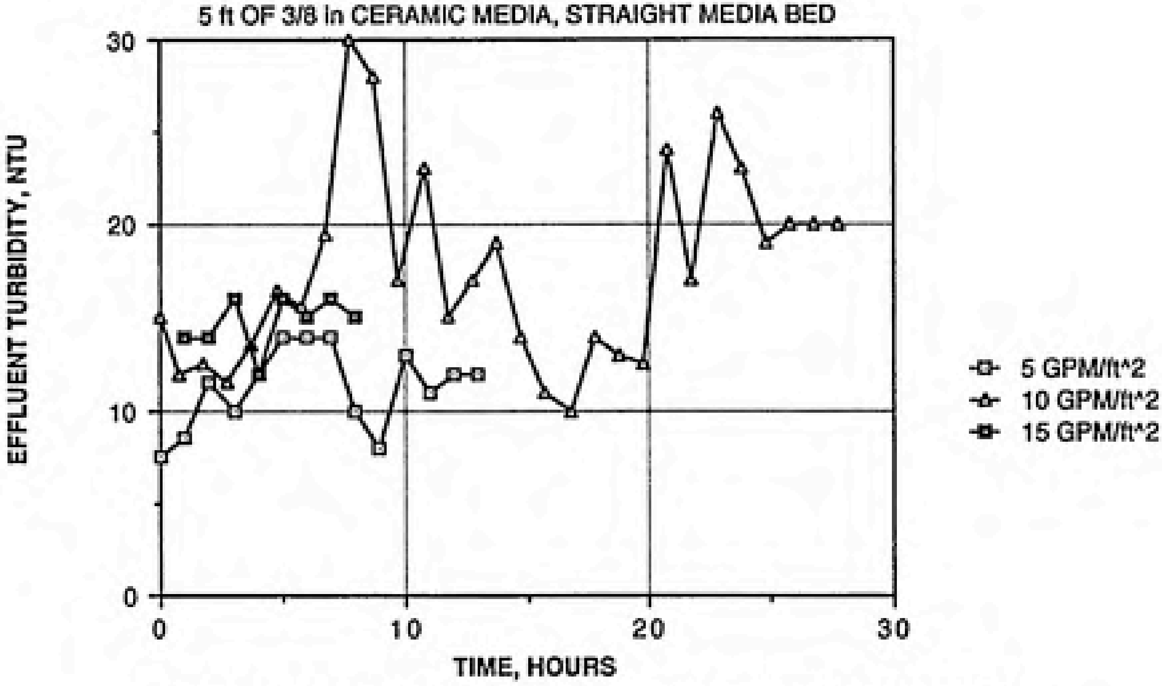


FIG. 4-11: INSTANTANEOUS EFFLUENT TURBIDITIES FROM FLOCCULATOR AT DIFFERENT LOADING RATES

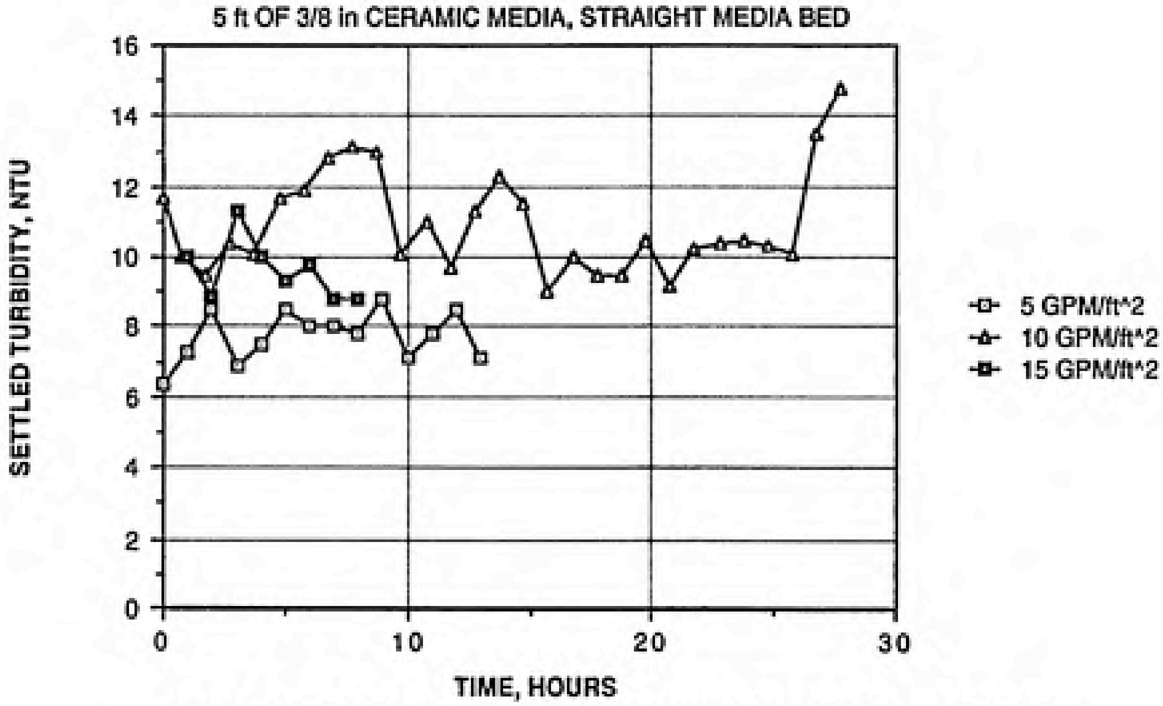


FIG 4-12: 20 MINUTE SETTLED EFFLUENT TURBIDITIES FROM FLOCCULATOR AT DIFFERENT LOADING RATES

TABLE 4-11: Summary of Extended Straight Bed Flocculation Run

Length of Run Hours	Flow rate GPM	Head loss mm	Velocity Gradient s^{-1}	Influent Turbidity NTU	Average Effluent Turbidity NTU	Average Settled Turbidity NTU
13.00	5	130-183	78-92	20	10.5	7.2
27.75	10	65-214	79-143	20	17.5	11.0
9.00	15	227-347	178-220	20	14.8	9.6

Ripening of the bed occurs after the bed has been used for flocculation for a period of time. Floc are entrapped in the interstitial spaces of the bed, lowering the porosity and increasing the head loss across the bed. Bed ripening impacts flocculator performance through this increase in head loss and the corresponding increase in the velocity gradient, and also by providing additional opportunities for collisions between particles and the entrapped floc. Head loss is the best available indicator of ripening For comparable flocculation runs, ripening should be considered as one factor in evaluating the results of the runs. The results from the run reported immediately above indicate that while flow rate is important in BCM flocculation, residence time and the ripened state of the bed might also be parameters to be considered.

Two flocculation runs designed to compare the performance of the two coagulants, ferric chloride and alum, used a five-foot column of 3/8-inch ceramic media. Water temperature for the run using ferric chloride was 10.5° C; the water temperature for the run using alum was 9 to 10° C. These flocculation runs were conducted at 10 GPM (10 GPM/ft^2 loading) using 11 mg/l of ferric chloride or 25 mg/l of alum. Polymer was not used as a coagulant aid during either of the runs. Comparisons of instantaneous and settled effluent turbidities are plotted in Figure 4-13 and Figure 4-14, respectively. A comparison of head loss build-up during the runs using the two coagulants is plotted in Figure 4-15. It should be noted in Figure 4-15 that the head loss began at a higher value in the run using ferric chloride because the bed was initially at a more ripened state in that run. This may have had a positive effect on the turbidities achieved with ferric chloride, particularly early in that run. The instantaneous and settled effluent turbidities show that the effluent water quality obtained by using ferric chloride was slightly better than that obtained using alum. From the instantaneous effluent turbidity results, ferric chloride seemed to produce a stronger floc which was more resistant to shearing during sampling than alum floc. It also appeared that ferric chloride floc settled better than alum floc. These benefits were achieved with a lower dosage of $FeCl_3$ than with alum. As a result, ferric chloride was used as the coagulant for all subsequent runs.

In conventional mechanical flocculation, the velocity gradient is used as a determinant of the effectiveness of flocculation. One concern of this study was to determine the relevance of the velocity gradient as a parameter controlling flocculation in a hydraulic flocculator such as the BCM unit. Three flocculation runs using a ripened five-foot straight bed of 3/8-inch ceramic media and lasting a total of 96 hours were used to analyze the effect of the velocity gradient. These particular runs were useful in analyzing the relationship between effluent turbidity and velocity gradient because the velocity gradient is constant throughout the entire depth of the bed when the straight bed configuration is used. Flow rates were 5, 7, 10 and 15 GPM; influent turbidity was 20 NTU; water temperature was 10 to 11° C; and 25 mg/l of alum was used

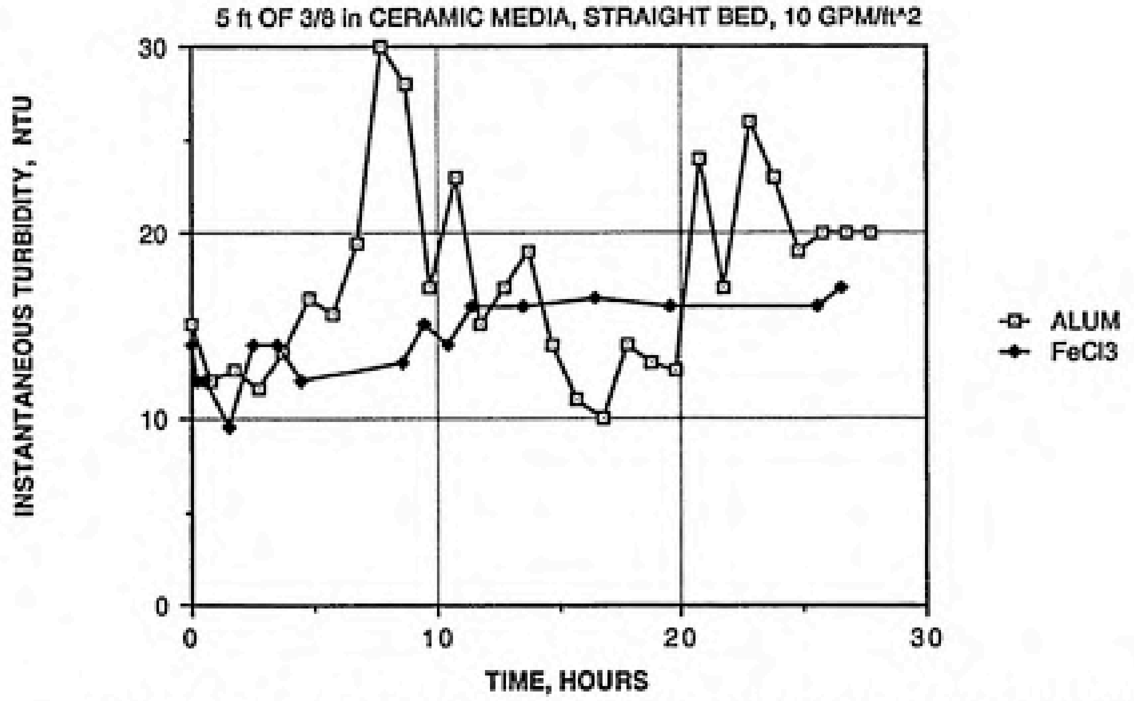


FIG. 4-13: EFFECT OF COAGULANT ON INSTANTANEOUS TURBIDITY FROM FLOCCULATOR

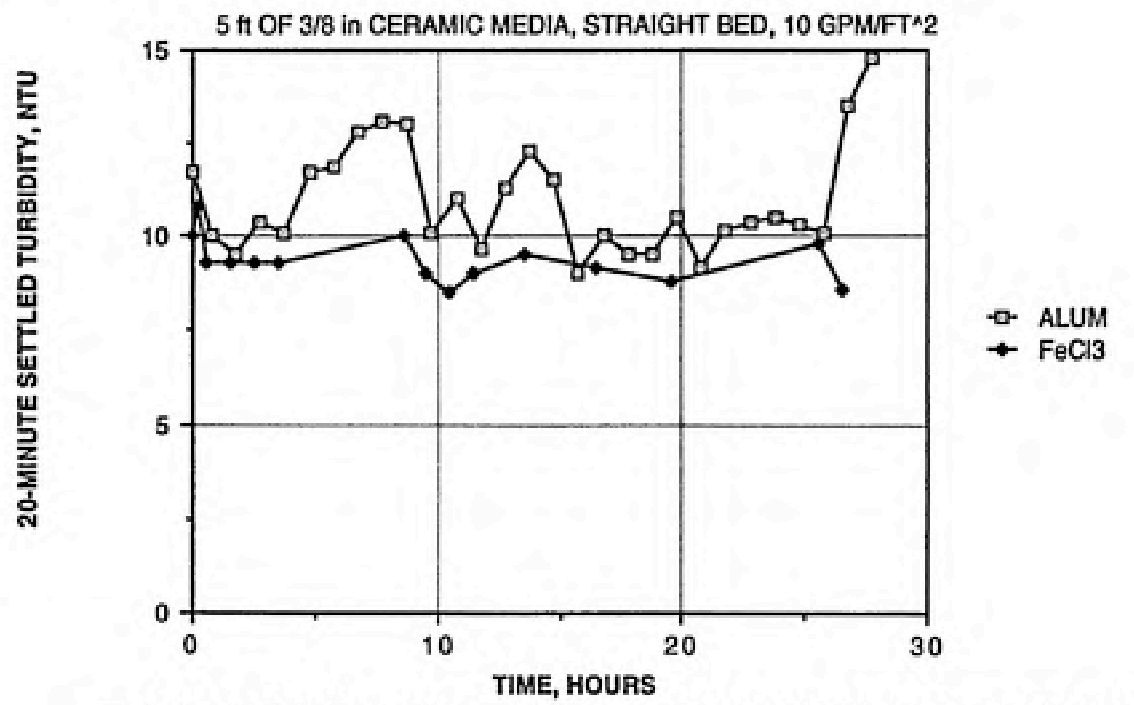


FIG. 4-14: EFFECT OF COAGULANT ON 20-MINUTE SETTLED TURBIDITY FROM FLOCCULATOR

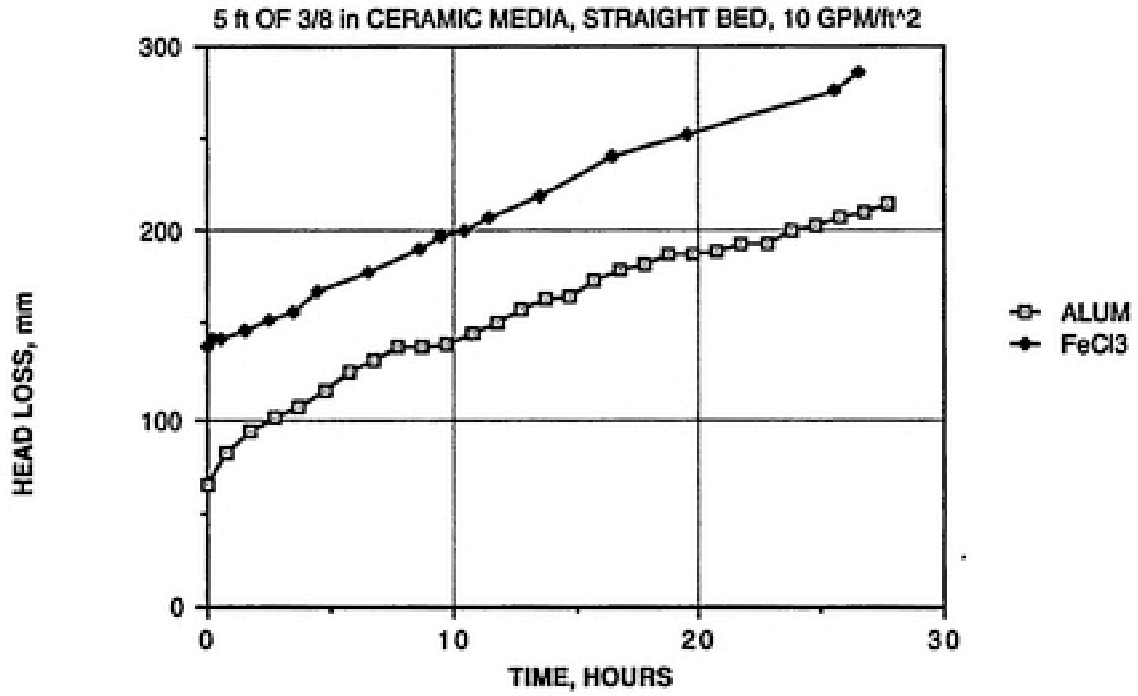


FIG. 4-15: EFFECT OF COAGULANT ON FLOCCULATOR HEAD LOSS

as the coagulant. Instantaneous effluent turbidity as a function of the calculated velocity gradient is plotted in Figure 4-16, and 20-minute settled turbidity as a function of the velocity gradient is plotted in Figure 4-17. For both plots, there is a great deal of scatter around the range of moderate velocity gradients from approximately 50 to 150 sec^{-1}. However, from the sample correlation coefficient, r, of 0.35 (r^2=0.12) in Figure 4-16 and the number of data points (80), the probability that there is a relationship between turbidity and the velocity gradient is greater than 0.995 (99.5%).[15]

Figures 4-18 and 4-19 plot the same instantaneous and settled turbidities as a function of the dimensionless parameter Gt - the velocity gradient multiplied by the residence time in the bed of media. Gt would tend to normalize the different flow rates because the lower flow rates, and corresponding lower velocity gradients, are at least partially offset by a longer residence time in the bed. Because of the large sampling (80 data points), the probability that there is a relationship between settled turbidity and Gt is greater than 0.9995 (99.95%).[15]

Calculated values of both the velocity gradient, G, and Gt used the clean bed porosity (α=0.4). Because there was no way of estimating porosity as a flocculation run progressed, the above comparison is a rough attempt to determine the effect of G or Gt on flocculator effluent turbidity. Additionally, the performance of the bed is associated with the mass of floc entrapped in the bed (which affects both porosity and the velocity gradient). The entrapped floc provide additional contact opportunities for particles, which are also not accounted for in the calculations of G and Gt.

Because none of the previous flocculation runs achieved a 20-minute settled turbidity of less than 2 NTU, the target settled turbidity, one of the last flocculation runs performed with the straight bed was intended to determine the

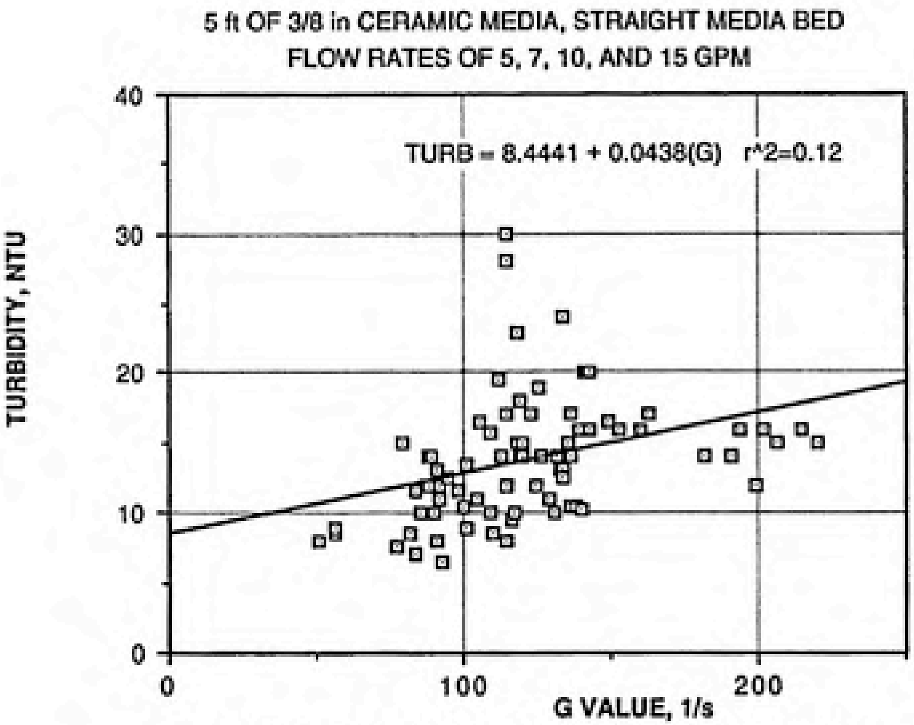


FIG. 4-16: EFFECT OF VELOCITY GRADIENT ON INSTANTANEOUS TURBIDITY

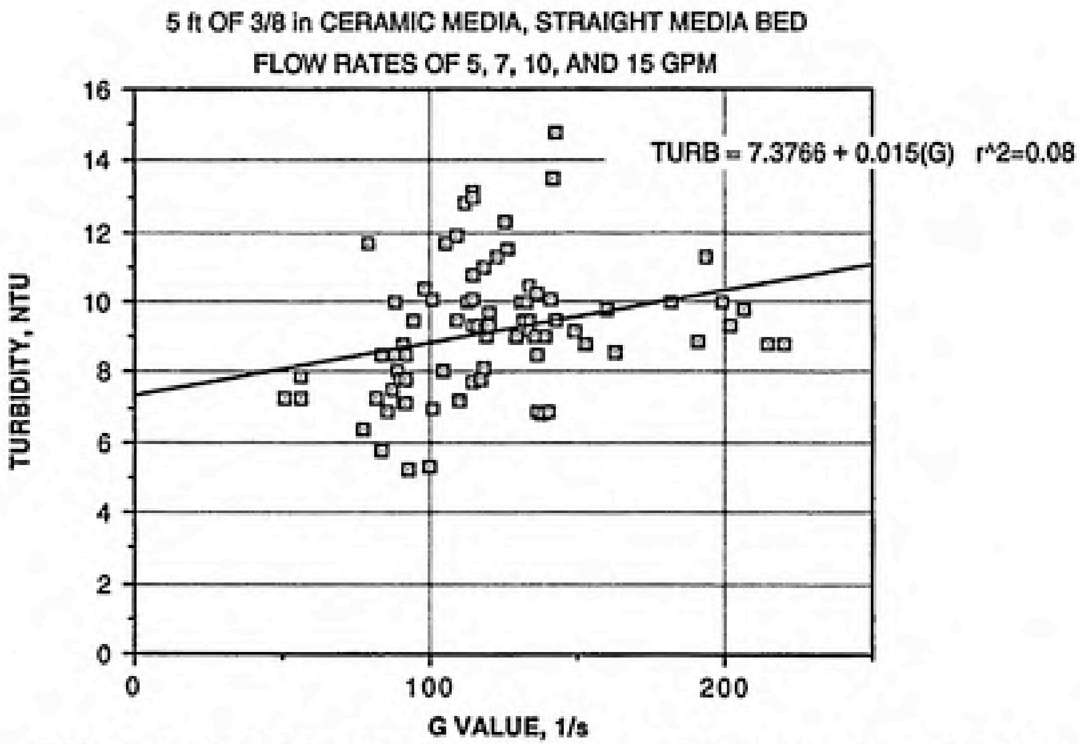


FIG. 4-17: EFFECT OF VELOCITY GRADIENT ON SETTLED TURBIDITY

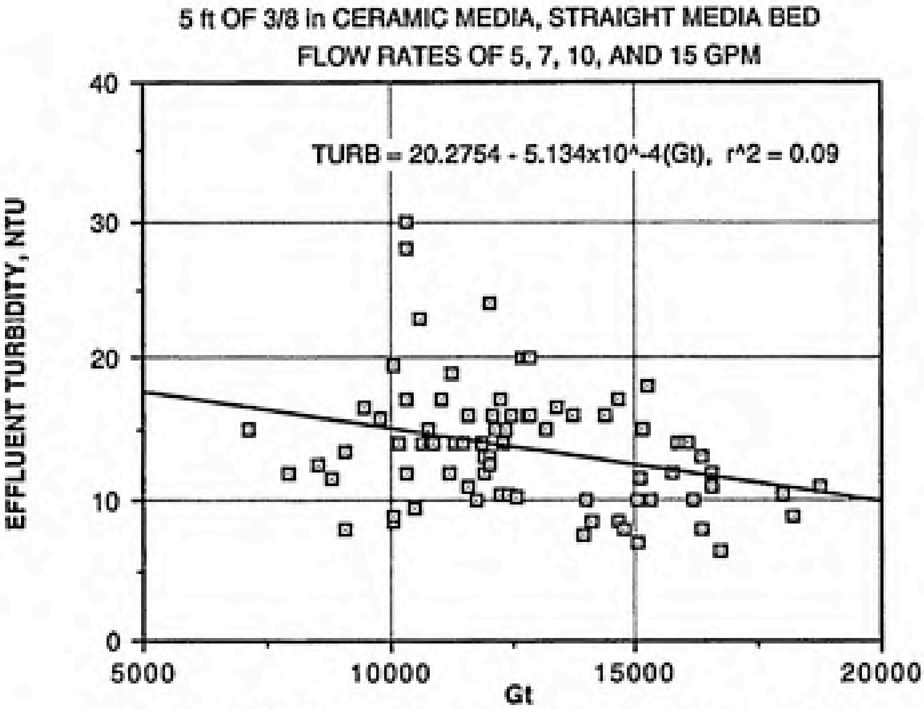


FIG. 4-18: EFFECT OF Gt ON INSTANTANEOUS TURBIDITY

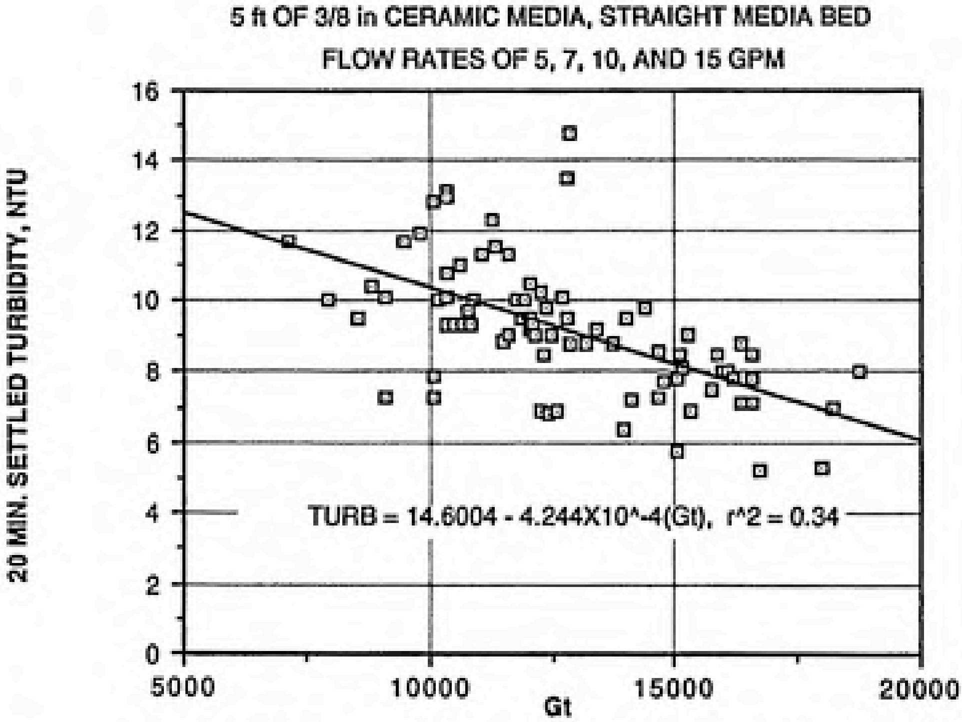


FIG. 4-19: EFFECT OF Gt ON SETTLED TURBIDITY

effect of upflow through packing in the overflow column following downflow through the flocculator. It was expected that the packed overflow column would operate in a manner similar to an upflow sludge blanket clarifier, with particles in the effluent from the flocculator being captured and built into larger floc within the void spaces of the media in the overflow column. The five-foot bed of 3/8-inch ceramic media, which had ripened during previous flocculation runs, was used in the flocculator (downflow); the overflow column (upflow) was packed with 4-1/2 feet of clean 3/4-inch Norpak media. The flow rate to the flocculator was 5 GPM (5 GPM/ft^2), and the loading rate to the overflow column was 10 GPM/ft^2. The water temperature for the run was 10.5° C. Eleven mg/l of ferric chloride was used as the coagulant dosage. It was not possible to measure head loss across the media in the overflow column because of the lack of taps in the design of the column.

The instantaneous and settled effluent turbidities from the flocculator are plotted in Figure 4-20; turbidities from the overflow column are plotted in Figure 4-21. This run produced the best quality water of any of the straight bed runs, with an average effluent from the overflow column of 6.0 NTU, settling to an average of 5.3 NTU after 20 minutes. While the target settled turbidity of 2 NTU was still not achieved, the effluent turbidity of the water from the overflow column, both instantaneous and settled, was well below what had been produced by any of the previous experiments using the flocculator alone. The variability in turbidity displayed by the overflow column can be attributable to limitations in the sampling technique in which a samples were dipped from the top of the column.

As anticipated, the overflow column operated as a sludge blanket clarifier. A large volume of floc was deposited on the high porosity Norpak media, and a layer of floc approximately six inches deep settled on top of the Norpak bed. As

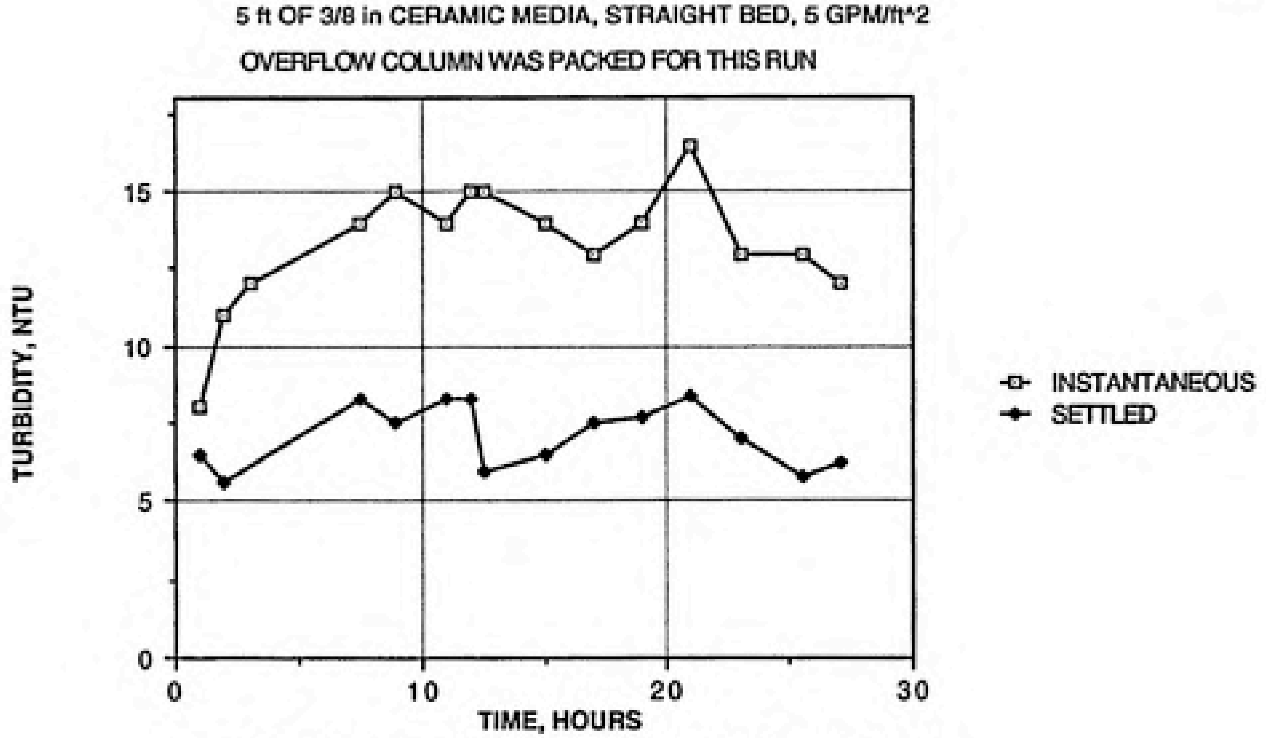


FIG. 4-20: TURBIDITY FROM FLOCCULATOR

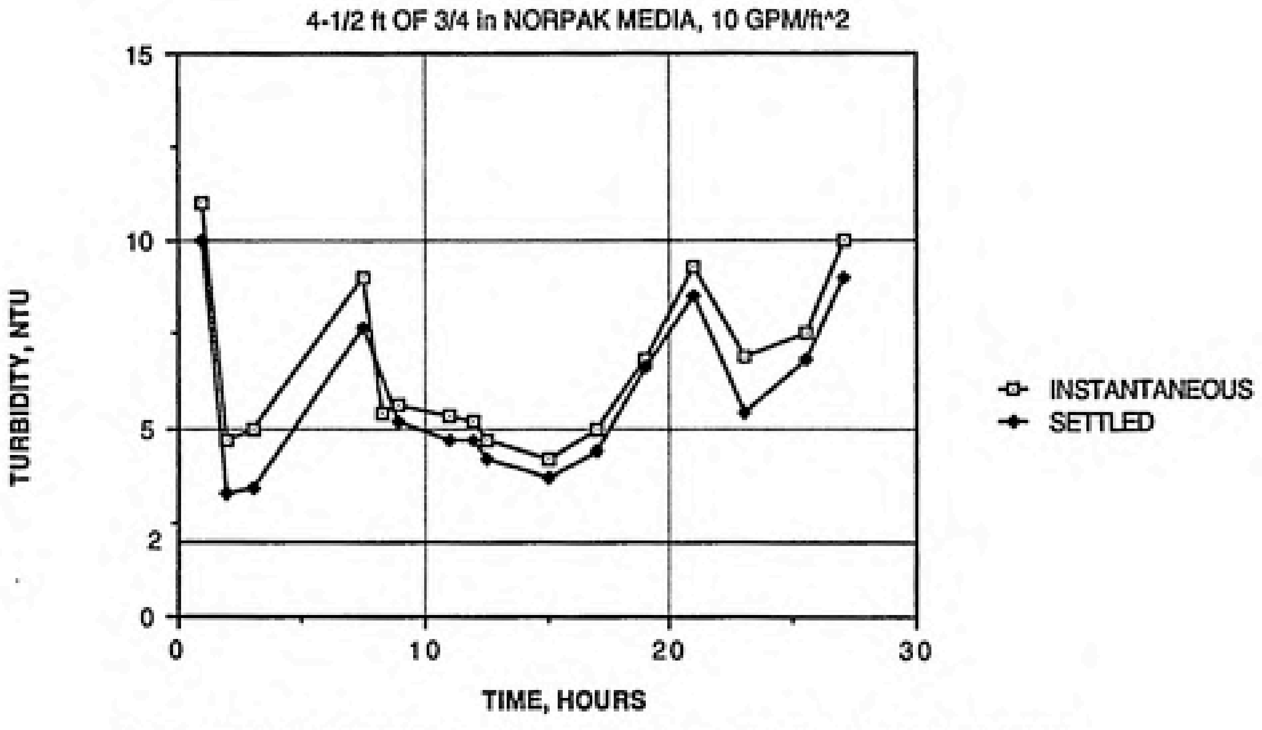


FIG. 4-21: TURBIDITY FROM PACKED OVERFLOW COLUMN

water flowed up through the ripened media and floc blanket, the particles and small floc were provided with opportunities for contacts and additional collisions. Larger floc from the floc blanket continuously broke away from the blanket and entered the overflow column effluent.

From the runs using the straight bed configuration in the flocculator, it was determined that:

1. Because air-impregnated ceramic and polypropylene media of similar sizes performed similarly, ceramic media would be a more economical media of choice;

2. Ferric chloride, rather than alum, was the preferred coagulant because it formed a stronger floc which was more resistant to shearing forces. These benefits were achieved at lower chemical dosages than were necessary with alum;

3. The flocculator performed better at lower hydraulic loading rates, on the order of 5 GPM/ft^2, compared to 10 GPM/ft^2. This was apparently due to the longer contact time in the bed at lower loading rates and lower shear forces at the lower interstitial velocities. However, ripening of the bed was also an important factor in improved flocculator performance;

4. With greater than 99.5% certainty, it was shown that there is a relationship between both the velocity gradient (G) and the dimensionless parameter Gt and turbidity from the flocculator. Unaccounted for in the calculations of G and Gt are the floc entrapped in the bed, which affect bed porosity and provide additional contact opportunities for particles;

5. While none of the straight flocculator media bed configurations tested achieved the target settled water turbidity of 2 NTU, upflow through Norpak media in the overflow column following downflow flocculation through the ceramic media bed exhibited the best potential for further clarifying the water.

This particular configuration achieved an average settled water turbidity of 5.3 NTU and individual values below 4 NTU.

2. **Tapered Bed Configuration**

A total of 14 tapered bed flocculation runs were performed. This type of hydraulic flocculation was intended to simulate conventional tapered mechanical flocculation by tapering the head loss and the associated velocity gradient as water flowed through the media. All tapered flocculation runs with one exception were performed with a stratified bed of ceramic media composed of 1-1/3 feet of 3/8-inch media over 1-2/3 feet of 1/2-inch media over 1-1/2 feet of 3/4-inch media.

Initially, this bed configuration was run for over 100 hours at high flow rates (13 and 15 GPM) to test the performance of the bed over an extended period of time. A flow rate of 15 GPM corresponds to a loading rate of 15 GPM/ft^2 at the top of the bed and 4.3 GPM/ft^2 at the bottom of the bed. One consequence of this extended run was that the water temperature varied from 11.6° C early in the run to 16.5° C in the later stages. The effect of water temperature on instantaneous and settled effluent turbidity is presented in Figures 4-22 and 4-23 respectively. There was a wide variation in the measured instantaneous effluent turbidities, which is probably a reflection of sampling technique. However, after 20 minutes of quiescent settling, the warmest water exhibited the lowest turbidity. In this case, the 16.5° C water had a turbidity of around 4 NTU after settling. As was demonstrated above under carefully controlled laboratory conditions while running jar tests (see Tables 4-3 through 4-5), mechanical flocculation is more efficient for warmer water. The improvement in effluent water turbidity with increasing temperature, as illustrated in Figure 4-23, confirms that this is also the case with BCM flocculation.

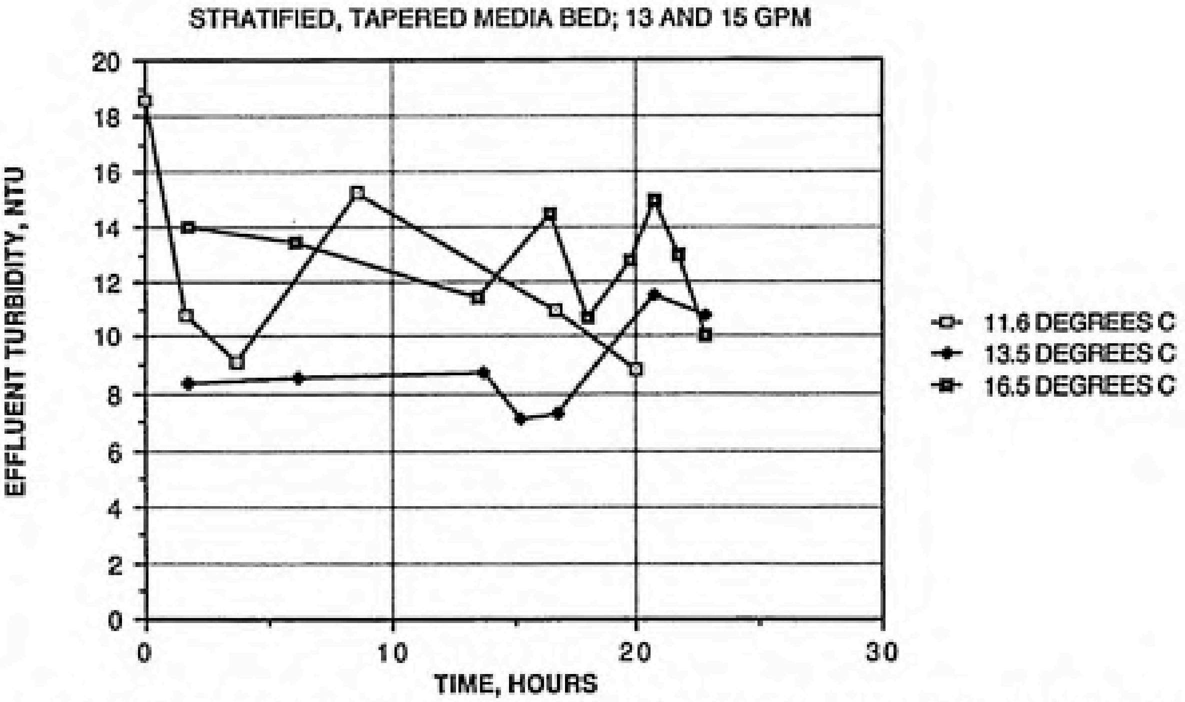


FIG. 4-22: EFFECT OF TEMPERATURE ON INSTANTANEOUS TURBIDITY

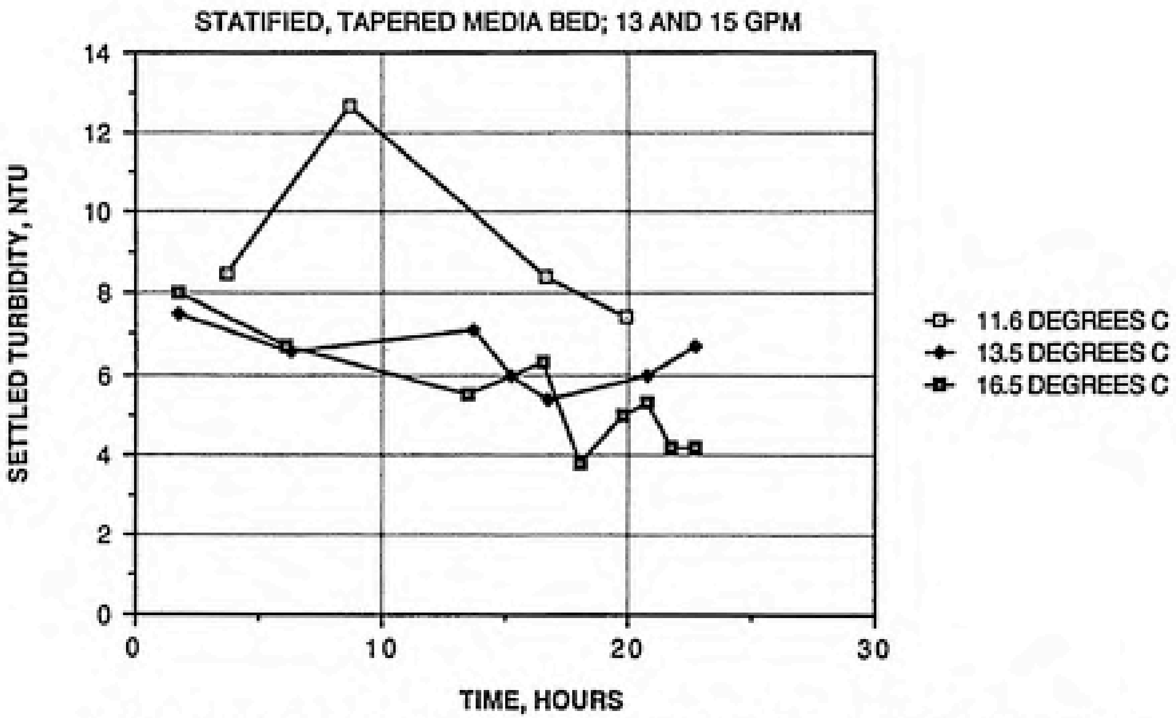


FIG. 4-23: EFFECT OF TEMPERATURE ON SETTLED TURBIDITY

The effect of varying the hydraulic loading rate to the flocculator is illustrated in Figure 4-24 and 4-25. These two graphs plot instantaneous effluent turbidity and 20-minute settled turbidity from the flocculator for runs conducted at 6 and 13 GPM with the tapered bed. A flow rate of 6 GPM corresponds to loading rates of 6 GPM/ft^2 at the top of the bed and 1.7 GPM/ft^2 at the bottom of the bed; the 13 GPM flow rate corresponds to loading rates of 13 GPM/ft^2 at the top of the bed and 3.7 GPM/ft^2 at the bottom of the bed. While the instantaneous turbidity results do not indicate conclusively that the lower flow rate is better, the settled water turbidity results tend to do so. With the exception of the last readings, when there were problems taking the effluent sample, the 6 GPM flow rate performed better. This reflects the longer contact time in the bed and lower shear forces for the lower hydraulic loading rate.

Figure 4-26 is a plot of the calculated velocity gradients in different parts of the bed for both flow rates. Due to the head loss caused by trapped particles during ripening of the bed, the velocity gradients in the middle and bottom sections of the bed are in the same range for both flow rates The velocity gradient in the top of the bed increases more rapidly during the 13 GPM run, especially during the latter portion of that run when settled water quality began to improve. This would tend to indicate a more rapid increase in head loss caused by the amount of particles trapped in the small media at the top of the bed.

One of the runs performed after the bed had ripened was intended to test the effect on flocculation of using polymer (Betz 1160P) as a coagulant aid when ferric chloride was used as the coagulant. Chemical dosages were 14 mg/l $FeCl_3$ and 0.3 mg/l polymer. A comparison of the run using polymer with the previous run in which polymer was not used is illustrated in Figures 4-27 and 4-28.

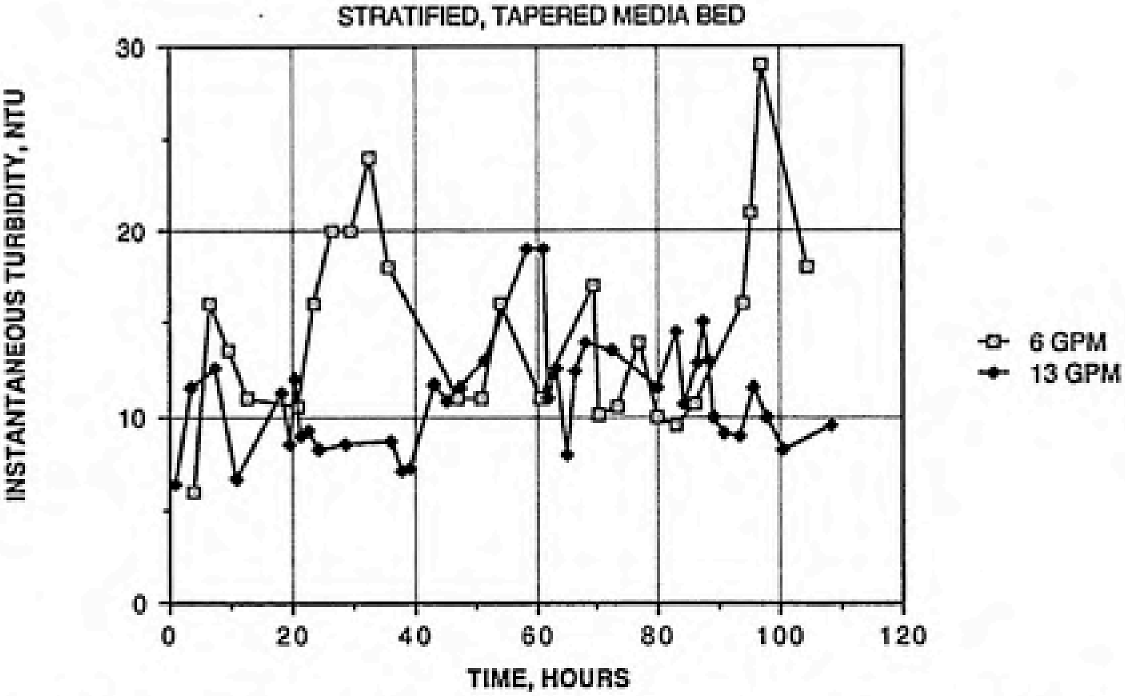


FIG. 4-24: EFFECT OF FLOW RATE ON INSTANTANEOUS TURBIDITY

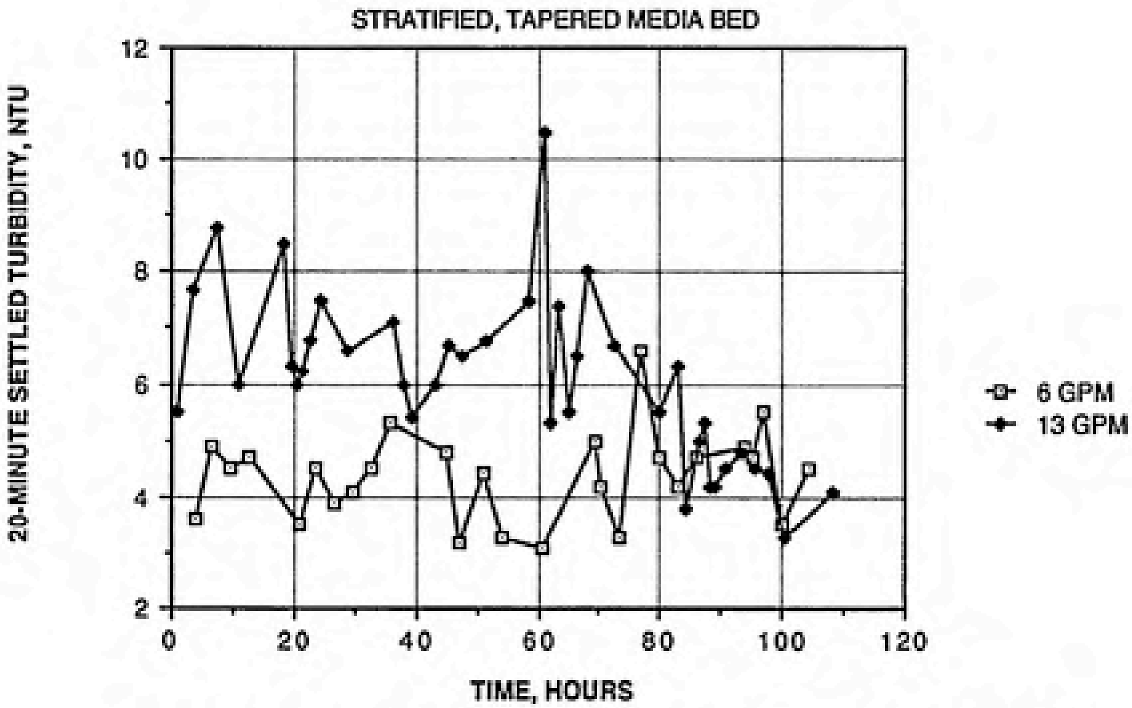


FIG. 4-25: EFFECT OF FLOW RATE ON SETTLED TURBIDITY

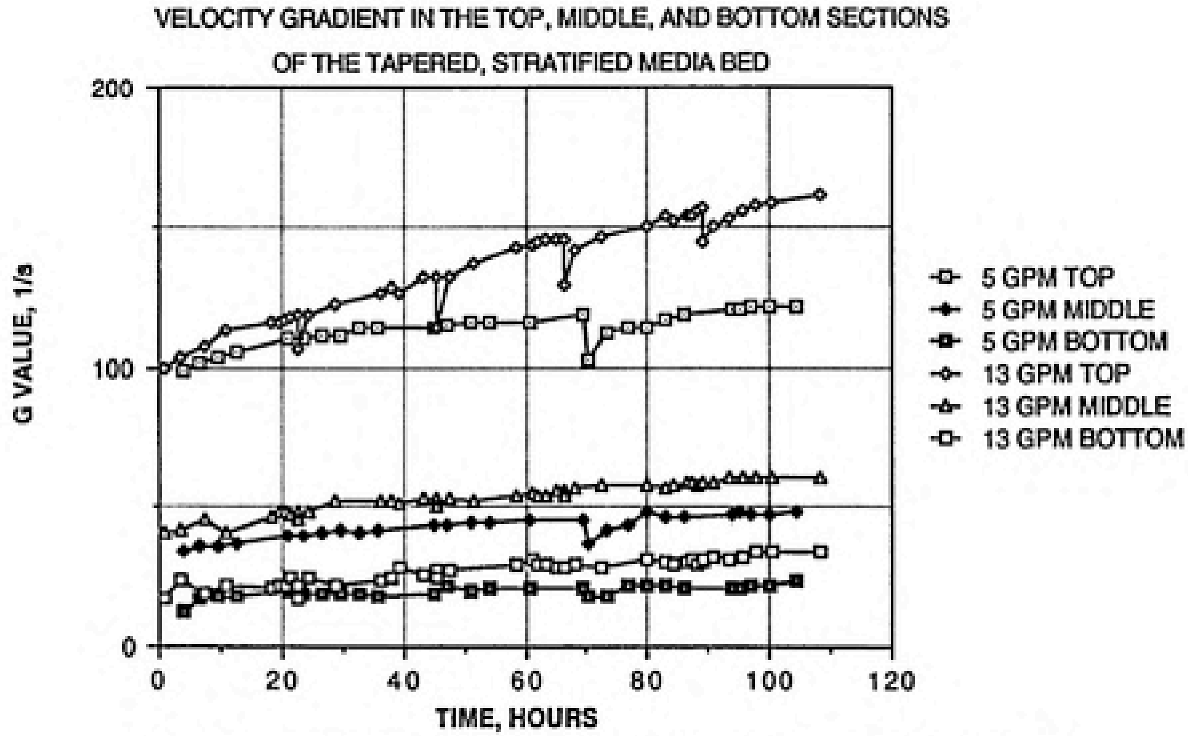


FIG. 4-26: EFFECT OF FLOW RATE ON VELOCITY GRADIENT

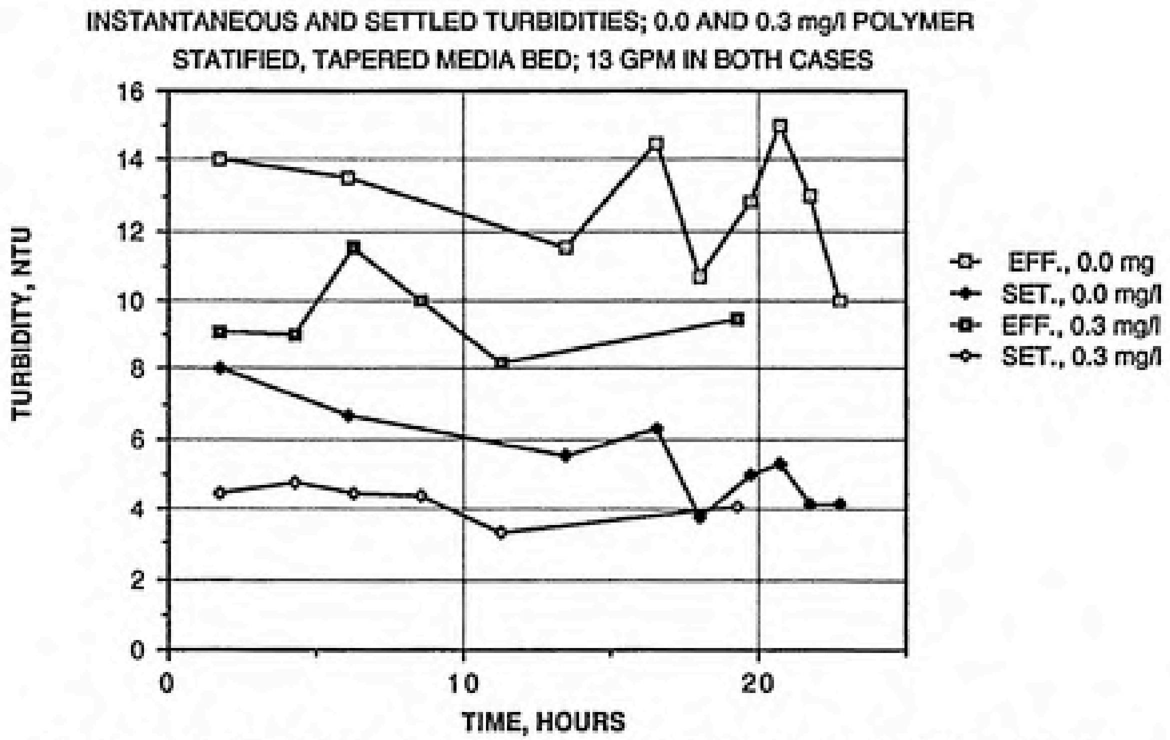


FIG. 4-27: EFFECT OF POLYMER ON FLOCCULATOR TURBIDITY

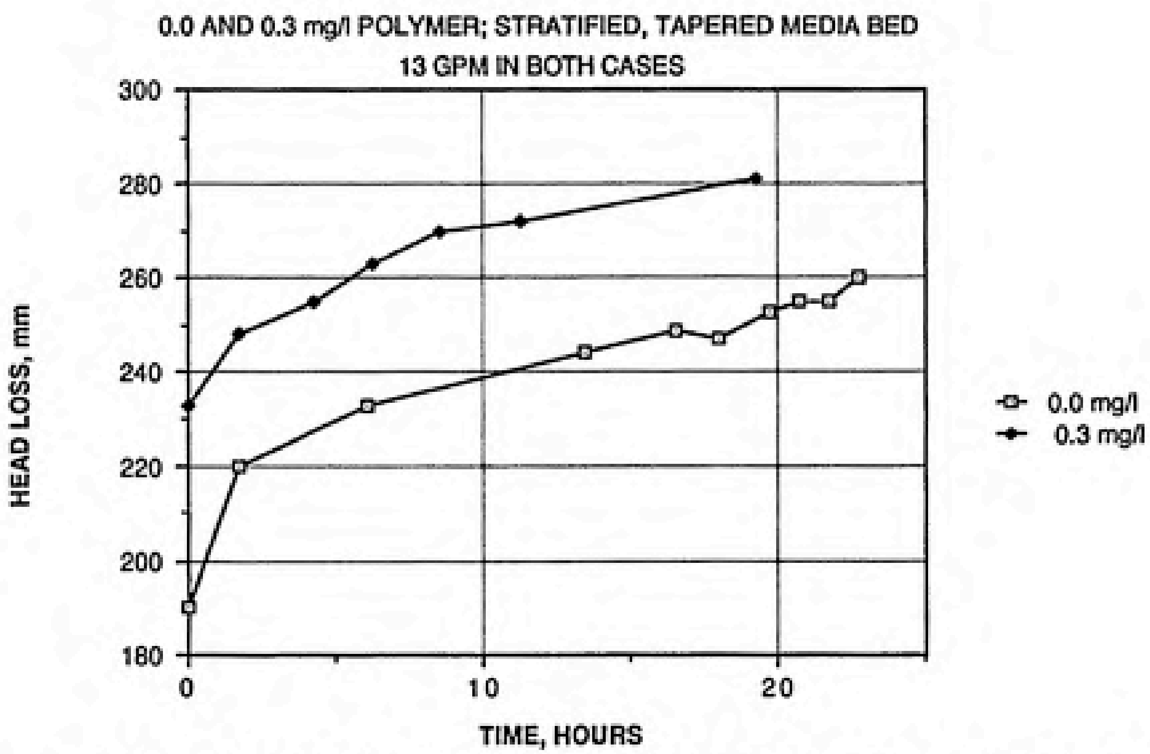


FIG. 4-28: EFFECT OF POLYMER ON OVERALL HEAD LOSS BUILD-UP

Influent water was also dosed with 14 mg/l of $FeCl_3$ in the run in which polymer was not used. Both runs were conducted at a flow rate of 13 GPM. Water temperature for the run in which polymer was not used was 16.5° C; for the run in which polymer was used the water temperature was 19° C. Figure 4-27 indicates that the instantaneous turbidity of the effluent water was lower when polymer was used. As shown in Figure 4-27, when polymer was not used, the settled water turbidity tended to be in the 4-6 NTU range, compared to settled water turbidities of 3-5 NTU when polymer was used. However, as indicated in Figure 4-28, the bed was initially riper in the run in which polymer was used. After approximately 18 hours of run time without polymer, the head loss across the bed had reach about the same level as the initial head loss for the run with added polymer. At this point, the settled water turbidity without polymer was equivalent to that achieved with polymer. It appeared that for equivalent head losses across the bed, polymer did not provide a better settled water turbidity. Additionally, head loss built at the same rate in both runs.

Near the end of the pilot tests using the tapered bed, two flocculation runs were conducted to test the effect of packing the overflow column with Norpak media. The first run was conducted at 8 GPM (8.0 GPM/ft^2 to 2.3 GPM/ft^2) and the second at 6 GPM (6.0 GPM/ft^2 to 1.7 GPM/ft^2). Both runs used 14 mg/l of $FeCl_3$ as coagulant. Water temperature was 19 to 20° C. Ripened ceramic media was used in the downflow BCM flocculator and 4-1/2 feet of clean 3/4-inch Norpak media was used in the overflow column. Results from these two runs are plotted in Figures 4-29 and 4-30, illustrating flocculator turbidity and overflow column turbidity, respectively. The settled turbidity from the downflow flocculator was consistently in the range of 4 to 5 NTU.

The loading rate to the overflow column varied from 16 GPM/ft^2 to 2.6 GPM/ft^2 during the first run and was 3.0 GPM/ft^2 throughout the second run.

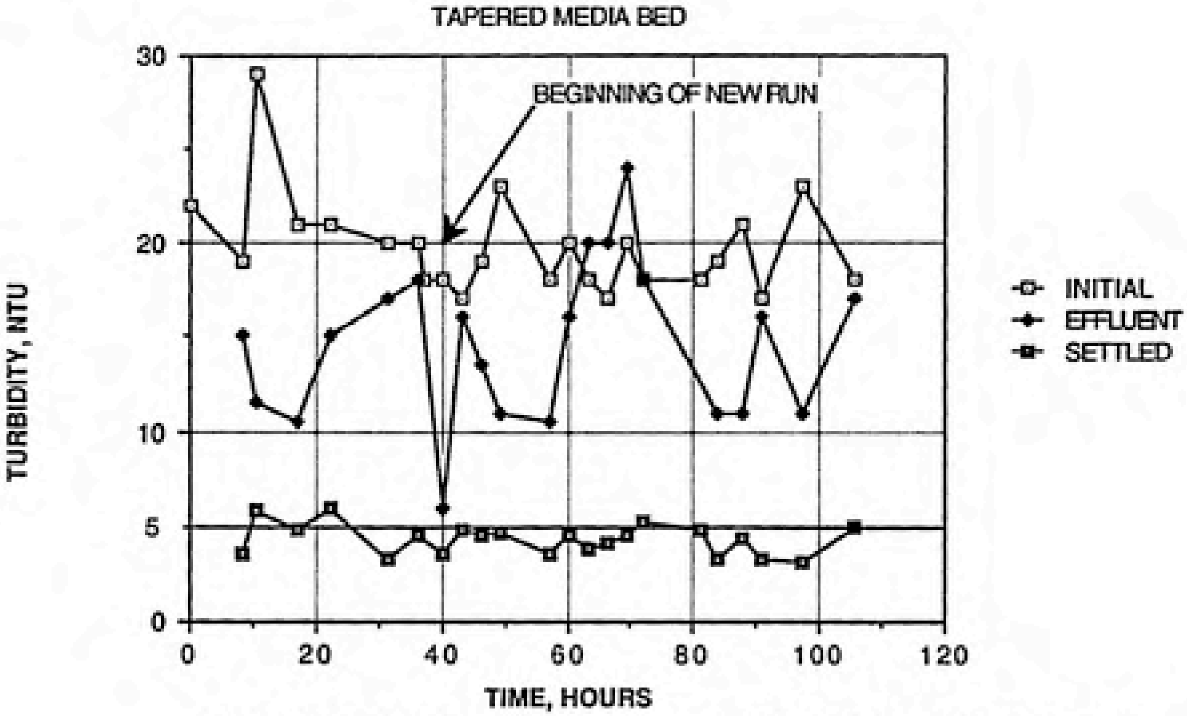


FIG. 4-29: FLOCCULATOR TURBIDITY PRIOR TO PACKED OVERFLOW COLUMN

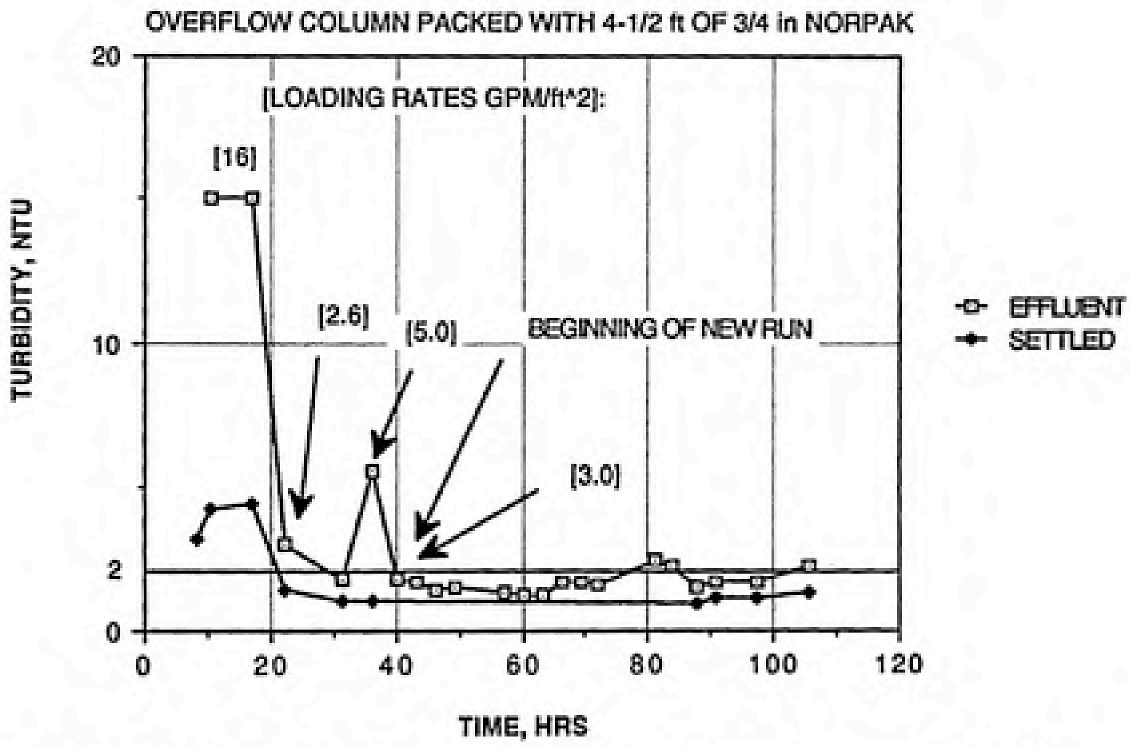


FIG. 4-30: TURBIDITY FROM PACKED OVERFLOW COLUMN

Except for the 16 GPM/ft^2 loading rate, excellent water quality, consistently below 2 NTU, was obtained from the settled effluent for the overflow column after initial ripening of the media (Figure 4-30). Loading rates $\leq$ 3 GPM/ft^2 provided the best settled water turbidity. Additionally, the settled water turbidity from both the flocculator and overflow column was stable over a wide range of test conditions. These were the first runs which achieved the goal of a settled water turbidity of less than 2 NTU. These two flocculation runs confirmed the earlier observations made when the overflow column was packed during the straight bed experiments, which was that allowing water to flow up through a packed overflow column improved water quality.

A comparison between the straight bed configuration with the packed overflow column and the tapered bed configuration with the packed overflow column is presented in Figures 4-31, 4-32, and 4-33. The flow rate for the straight bed was 5 GPM (5 GPM/ft^2) and the loading rate in the overflow column was 10 GPM/ft^2. The flow rate for the tapered bed was 6 GPM (6 GPM/ft^2 at the top of the bed and 1.7 GPM/ft^2 at the bottom of the bed) and the loading rate in the overflow column was 5 GPM/ft^2. As expected, the straight bed configuration for the flocculator did not perform as well as the tapered bed configuration (Figure 4-31). The tapered bed configuration produced water that settled to less than 5 NTU. Additionally, the tapered bed accumulated head loss faster than the straight bed (Figure 4-33), indicating more rapid ripening. The overflow column also provided better performance when used in conjunction with the tapered downflow bed (Figure 4-32). This suggests that because the straight bed did not produce settleable floc as effectively as the tapered bed, the packed overflow column was not as efficient in agglomerating the floc into larger particles.

However, other factors were involved in the relative performance of the two flocculator configurations. The hydraulic loading rate to the overflow

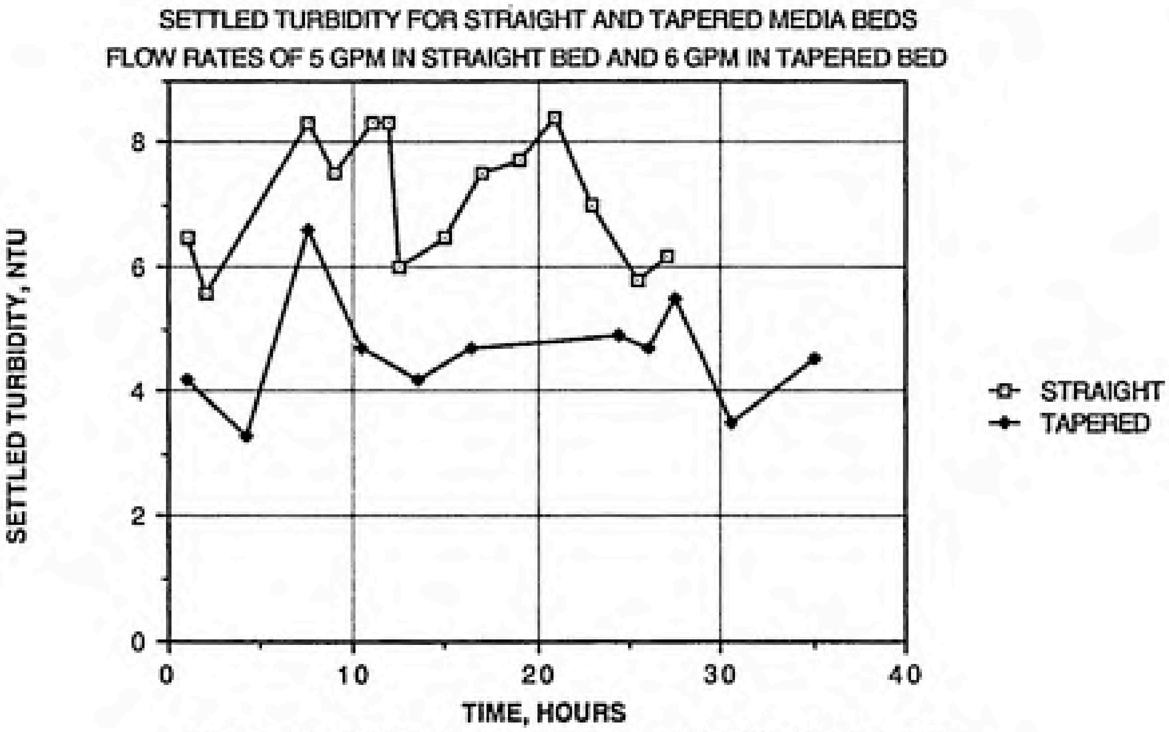


FIG. 4-31: EFFECT OF BED CONFIGURATION ON 20-MINUTE SETTLED TURBIDITY

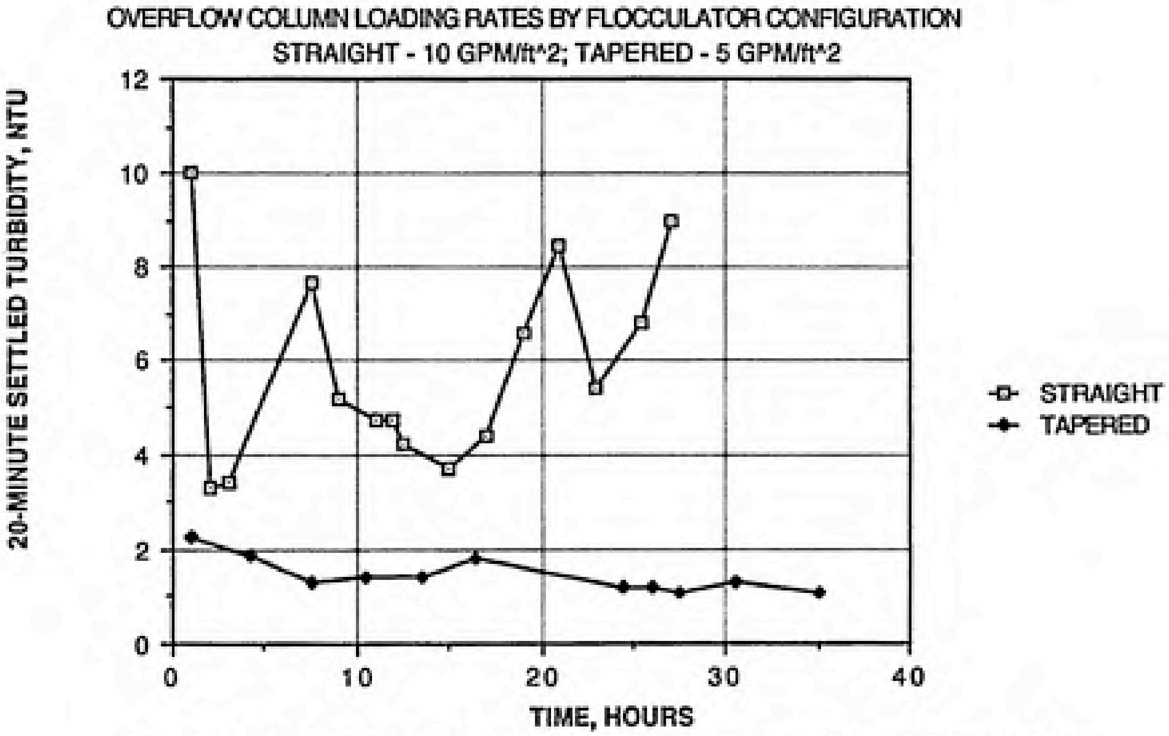


FIG. 4-32: EFFECT OF FLOCCULATOR CONFIGURATION ON 20-MINUTE SETTLED TURBIDITY FROM OVERFLOW COLUMN

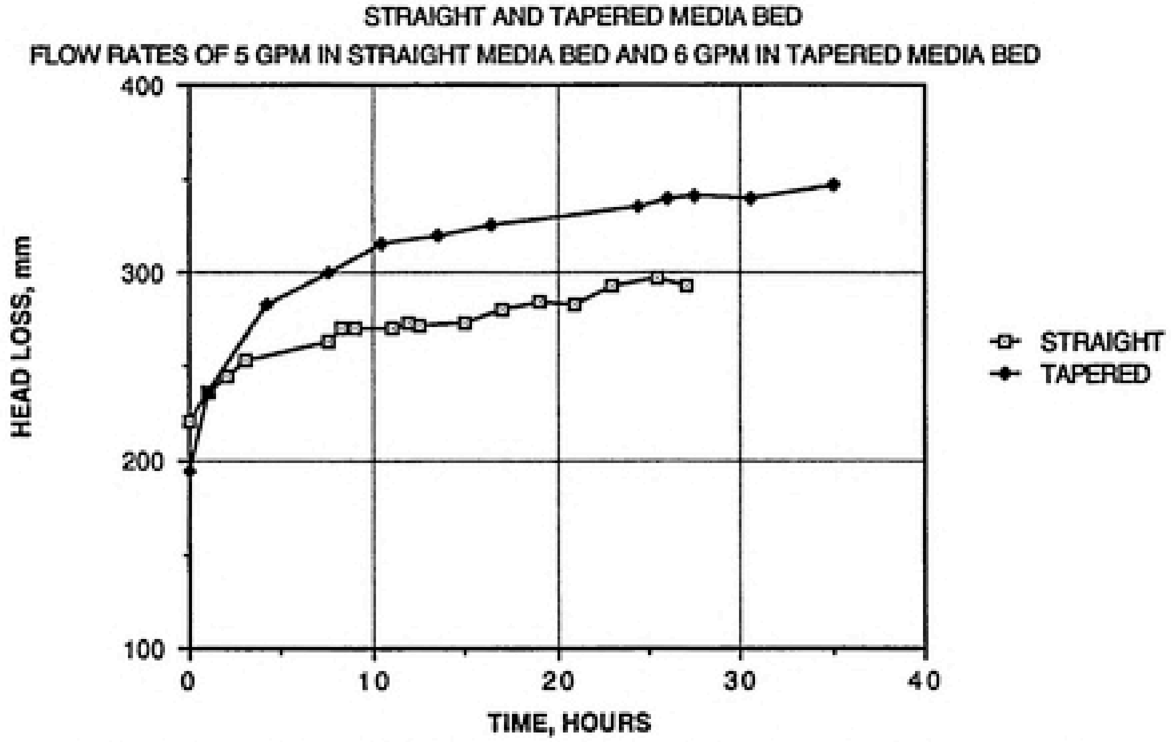


FIG. 4-33: EFFECT OF FLOCCULATOR CONFIGURATION ON HEAD LOSS

column was much higher when the straight bed was used in the flocculator (10 GPM/ft^2 versus 5 GPM/ft^2). Because these runs occurred at different times of the year, the straight bed flocculation run was conducted with 10.5° C water while the tapered bed was run with 20.5 to 22.0° C water. In addition, there was less total media (by volume) in the straight bed (5 ft^3) than in the tapered bed (10.3 ft^3). The differences in hydraulic loading rates, water temperature, and media bed volumes were sufficiently meaningful to prevent a true comparison of the two different configurations of the pilot plant

After the success of using Norpak media in the upflow configuration of the overflow column following downflow tapered flocculation with ceramic media, a flocculation run was performed at 6 GPM on a tapered bed of 1-1/3 feet of 3/8-inch ceramic media over 1-2/3 feet of 1/2-inch ceramic media over 1-1/2 feet of 3/4-inch Norpak media, all downflow in the flocculator. In this case, the overflow column was not packed with media; instead, Norpak media was the bottom layer of the stratified bed in the downflow flocculator. Like all the previously tested downflow configurations, this particular media arrangement was not able to produce an effluent water of less than 2 NTU after 20 minutes of settling; the best 20-minute settled turbidity using this bed configuration was 2.9 NTU. Additionally, after running the bed for 100 hours, the Norpak layer at the bottom of the bed separated from the upper ceramic layer due to the weight of floc captured by the Norpak. Bed separation makes this particular configuration impractical.

From the above presentation of tapered bed flocculation results, the following conclusions can be reached:

1. The flocculator configuration of a tapered bed using stratified media performed better at creating settleable floc than any other configuration tested.

However, the best settled water turbidity consistently produced by the flocculator in this configuration was 3 to 4 NTU;

2. Water temperature and run time for a particular media had pronounced effects on flocculation efficiency, with the best flocculation runs occurring with warmer influent water and with a ripened bed;

3. The addition of polymer as a coagulant aid did not sufficiently improve the performance of the tapered bed configuration when $FeCl_3$ was used as the coagulant;

4. Placing Norpak media in the overflow column following downflow flocculation through tapered and stratified ceramic media produced settled water turbidity ≤ 2.0 NTU. This result was achieved consistently for a hydraulic loading rate in the overflow column of ≤ 3 GPM/ft^2.

This series of flocculation experiments was performed a model water using kaolin as the turbidity source. Because influent conditions to the flocculator were carefully controlled, the results obtained during this study need to be verified on a real water. The effect of water temperature and hydraulic loading rate on flocculator performance should be studied. Also to be studied would be the effect of loading rate on the performance of the overflow column. A more definite comparison between straight and tapered bed flocculator configurations should be performed. Because the best results during this study were obtained with the tapered bed in the flocculator followed by the packed overflow column, this configuration is the best starting point for the field study.

Other possible areas of study for the BCM flocculator are as a roughing filter or in direct filtration. The purpose of a roughing filter is to remove suspended solids from a water to be filtered and consequently reduce the solids loading on the filter. The BCM flocculator was able to perform this function on an influent water with a turbidity of 20 NTU by agglomerating the particles into floc and trapping floc in the bed of media. Direct filtration is a water treatment process in which effluent water from the flocculation basins flows directly onto the filters without first going through sedimentation basins. The AWWA recommends a raw water of ≤ 5 NTU for direct filtration plants, although such plants have been constructed when the plant influent was as high as 12 to 16 NTU.[16] Current practice involves production of a pin-point floc through flocculation times of approximately 10 minutes at velocity gradients of up to 100 s^{-1}.[16] Research into using the BCM flocculator for direct filtration would need to focus on its production of large floc and retention times of one to five minutes, depending on loading rate. The BCM flocculator was capable of establishing velocity gradients of ≥ 100 s^{-1}.

V. SUMMARY AND CONCLUSIONS

This pilot plant study investigated the feasibility of the buoyant coarse media (BCM) flocculation concept. The variables which were studied were type of media, size of media, hydraulic loading rates, stratification and depth of the media bed, configuration of the bed (straight or tapered), chemicals (both coagulants and polymer), and water temperature. The tests conducted during this study were run using a model water suspension of kaolinite clay. Evaluation of the results obtained during this pilot plant study of the BCM flocculator led to several conclusions which are discussed below. Among the conclusions are the validity, as well as the limitations, of the BCM flocculation concept, the best flocculator configuration developed during this study, the need for further study, and the engineering implications of this design.

This study established that hydraulic flocculation can be accomplished using a bed of buoyant coarse media operated in a downflow mode. Visual confirmation of flocculation was provided by the formation and deposition of floc within the bed and by the increase in head loss across the bed and the appearance of floc exiting the bed as ripening of the bed progressed. The degree to which flocculation occurred and the instantaneous and settled water turbidities of the effluent depended on the media, the bed configuration, the loading rate, chemicals and chemical dosage, the degree of bed ripening, and water temperature.

Water quality, as measured by instantaneous and settled flocculator effluent turbidity, generally improved during the course of flocculation runs as the bed of media ripened and head loss increased. Twenty-minute settled water turbidities below 4 NTU were achieved with an influent water turbidity of 20 NTU when the flocculator was operated with a tapered, stratified bed of ceramic media, ferric chloride was used as the coagulant, and the water temperature was in the range of 20-22° C. These were the optimal configuration and operating conditions when only the flocculator was packed with media. A relationship was found between the velocity gradient (calculated from the head loss and flow rate) and effluent turbidity. A relationship was also found between Gt and effluent turbidity.

The main limitation to this mode of operation was that 20-minute settled water turbidities below 2 NTU could not be achieved using only the flocculator. This value for settled water turbidity was considered important because 2 NTU is an acceptable turbidity for water leaving sedimentation basins and entering filters of conventional water treatment plants. However, in flocculation runs in which the effluent from the tapered BCM flocculator was allowed to flow up through the packed overflow column, the effluent from the overflow column consistently settled to a turbidity of less than 2 NTU when the hydraulic loading rate in the overflow column was ≤ 3 GPM/ft^2. This indicated that a downflow BCM flocculator followed by an upflow packed bed column constituted the best operational design.

The optimal configuration for the flocculator determined by this study was with an inclined wall and stratified bed of media, producing a continuum of velocity gradients as water flowed through the bed. Air-impregnated ceramic media (from 3M Chemical Co. of St. Paul, MN) proved to be the best choice, based on its performance and its lower cost in relation to other types of media. The best flocculator configuration used was a tapered bed, stratified with 1-1/3 feet of 3/8-inch media over 1-2/3 feet of 1/2-inch media over 1-1/2 feet of 3/4-inch media. The upflow contact clarifier produced by packing the overflow column with Norpak media was critical in meeting the performance objectives of the pilot plant. Only high porosity Norpak media (from NSW Corp. of Roanoke, VA) was tested in the overflow column because the large interstitial spaces in that type of media was believed to be necessary to capture floc from the flocculator effluent. The best choice of coagulant, based on jar tests and flocculation runs, proved to be ferric chloride. Ferric chloride appeared to form a more shear-resistant floc, required a lower chemical dosage, and did not require a coagulant aid, when compared to alum.

This combination of tapered and stratified media in the downflow mode, packed overflow column in the upflow mode, and ferric chloride coagulant was capable of producing the desired 20-minute settled water turbidity of less than 2 NTU. The hydraulic loading rates which provided the best results were 6 to 8 GPM downflow in the BCM flocculator (6 GPM/ft^2 to 8 GPM/ft^2 at the top of the bed of media and 1.7 GPM/ft^2 to 2.3 GPM/ft^2 at the bottom of the bed) and $\leq$ 3 GPM/ft^2 upflow in the overflow column, which are higher loading rates than conventional flocculators and sludge blanket clarifiers. Conventional flocculators have hydraulic loading rates of 4 to 8 GPM/ft^2; and conventional sludge blanket clarifiers are loaded at 0.85 to 1.28 GPM/ft^2.[3] The theoretical retention times in the BCM flocculator at these loading rates were 9 to 13 minutes, compared to retention times of 15 to 30 minutes in conventional mechanical flocculators.[3] The theoretical retention time in the overflow column at a loading rate of 3 GPM/ft^2 was nine minutes, compared to 20 minutes in the flocculation region of a conventional sludge blanket clarifier.[3]

Further study is necessary in order to verify the BCM flocculation system on a real water. Use of coagulated raw water from an operating water treatment plant is the best way to test the system under real conditions. The effect of water temperature, chemical dosages, and background organic material on flocculation could then be studied, leading to a determination of the optimal BCM flocculator and overflow column configuration for a particular raw water. This was done in a series of studies at two local water treatment plants in Carrboro and Durham, NC, and is the subject of another Master's Report (Gandley, 1992).

Several commercial applications for this process are possible. Existing flocculation basins could be retrofitted with buoyant media to upgrade their hydraulic capacity as part of a total plant capacity upgrade. Additionally, this process could have applications for small community water systems or for developing countries due to its relatively small size and footprint, low energy requirements, and absence of mechanical parts.

REFERENCES

1. Okun, Daniel and Christopher Schulz, "Hydraulic Flocculation," Chapter 6 of Surface Water Treatment for Communities in Developing Countries, Wiley: New York, 1984.
2. Amirtharajah, Appiah and Charles R. O'Melia, "Coagulation Processes: Destabilization, Mixing, and Flocculation," Chapter 6 of Water Quality and Treatment, ed. by Frederick W. Pontius, McGraw-Hill: New York, 1990.
3. James M. Montgomery, Consulting Engineers, Inc., Water Treatment Principles and Design, Wiley: New York, 1985.
4. O'Melia, Charles R., "Coagulation and Flocculation," Chapter 2 of Physicochemical Process for Water Quality Control, ed. by Walter J. Weber, Jr., Wiley: New York, 1972.
5. Stumm, Werner and James J. Morgan, "Chemical Aspects of Coagulation," *Jour. AWWA* , 54:8:970 (Aug. 1962)
6. Friedlander, S. K., "Collision and Coagulation," Chapter 7 of Smoke, Dust, and Haze: Fundamentals of Aerosol Behavior, Wiley: New York, 1977.
7. Camp, Thomas R. and P. C. Stein, "Velocity Gradients and Internal Work in Fluid Motion" from Civil Engineering Classics: Outstanding Papers of Thomas R. Camp, ASCE: New York, 1973.
8. Hudson, Herbert E., Jr., "Physical Aspects of Flocculation," *Jour. AWWA*, 57:7:885 (Jul. 1965)
9. Hudson, H. E., Jr. and J. P. Wolfner, "Design of Mixing and Flocculating Basins," *Jour. AWWA*, 59:10:1257 (Oct. 1967)
10. Hudson, Herbert E., Jr. Water Clarification Processes. Reinhold: New York, 1981.
11. Han, Mooyoung and Desmond F. Lawler, "The (Relative) Insignificance of G in Flocculation" Unpublished article, submitted to Journal of the American Water Works Association.
12. Ayoub, George M. and Faten F. Nazzal, "Gravel Packed Baffled Channel Flocculator," *Jour. of Environmental Engineering*, 114:6:1448 (Dec. 1988)
13. Haberer, Klaus and Sabine Normann-Schmidt, "The Haberer Process: Combining Flocculation, Filtration, and PAC Adsorption," *Jour. AWWA*, 83:9:82 (Sep. 1991)
14. Levenspiel, Octave, Chemical Reaction Engineering, Wiley: New York, 1972.
15. Dixon, Wilfrid J. and Frank J. Massey, Jr., Introduction to Statistical Analysis. McGraw-Hill: New York, 1983.
16. Cleasby, John L, "Filtration," Chapter 8 of Water Quality and Treatment, ed. by Frederick W. Pontius, McGraw-Hill: New York, 1990.

APPENDIX A:

Monthly Reports Submitted During Laboratory Study

CDM
environmental engineers, scientists, planners, & management consultants

CAMP DRESSER & McKEE INC.
7535 Little River Turnpike, Suite 200
Annandale, Virginia 22003
703 642-5500

October 19, 1990

Eimco Process Equipment Company
669 West Second South
Salt Lake City, Utah 24110-0300
Attn: Stan Heden

RE: Buoyant Media Flocculation Research Project

Dear Stan:

Please find attached the progress report for September 1990, prepared by Dr. Phil Singer of the University of North Carolina. Photographs are also enclosed of the pilot flocculator unit and related equipment.

The status of the project can be summarized as follows:

- o Three graduate students are currently working on the project: Michael Hacker, a second-year graduate exchange student from West Germany (full-time); Jim Nix, a first-year graduate student (1/2-time); and Bob Gandley, a first-year graduate student (1/2-time). Mike will be on the project through February 1991. The others will be on the project through its completion.

- o The start-up period for the project has taken longer than originally planned. Certain equipment items (raw water pump, pumpheads, mixers, fittings, flowmeters) were installed, tested and then replaced to allow for higher flowrates through the flocculator unit. Minor leaks in the flocculator unit had to be repaired by Atlantic Plastics. The support system for the pilot unit was redesigned to prevent the sidewalls from bowing. We expect that initial pilot test runs will now commence the week of October 24, 1990.

- o Six types of buoyant media have been selected for testing:

  - 1/2-inch polypropylene solid spheres w/ air bubble
  - 1/4-inch polypropylene solid spheres w/ air bubble
  - 1/2-inch ceramic spheres (3M Macrolite)
  - 1/4 to 1/2-inch ungraded ceramic spheres (3M Macrolite)
  - 5/8-inch NORPAC polyethelene packing
  - 1-inch TRIPAC polyethelene packing

  Six cubic feet of each media type has been ordered and shipped to the testing site.

- o Jar testing and development of dosage calibration curves for the feed water has begun and will continue for another week or so.

- o The testing protocol has been revised to allow the six alternative media types to be screened initially (rather than later in the testing protocol) in a series of preliminary pilot tests. Based on these test results, 1-2 media types will be selected for subsequent testing to optimize the BCM flocculation process. The following criteria will be used to evaluate the media:

  - The ability to reach head loss stabilization across bed
  - Time to reach head loss stabilization
  - Residence time distribution
  - Floc formation characteristics
  - Ease of bed cleaning (via air scour and doubling the flowrate through the bed).

Since our project kickoff meeting last June, I have made two visits to the University of North Carolina in August and September 1990 to meet with Dr. Singer and the graduate students working on the project and to assemble the pilot flocculator unit. My next visit is scheduled for November 1 and 2, 1990.

If you have any questions on this progress report, please give me a call.

Sincerely,

[redacted]

Christopher R. Schulz, P.E.

cc. Dr. Phil Singer, UNC
P.W. Prendiville, CDM
J.C. Thompson, CDM

MONTHLY PROGRESS REPORT / BOUYANT COARSE MEDIA FLOCCULATOR

SEPTEMBER, 1990

Most of the work done this month involved assembly and modifications of the pilot plant:

-changed out 1/4 HP pump to 3/4 HP;
-changed out 3/4" static mixers to 1" mixers;
-test run with new pump and mixers indicated that the maximum flow rate with the two mixers was only 13 gpm, and 17 gpm with only one mixer;
-ordered 2" static mixer from Koflo to be place after the alum and acid/base addition point;
-several fittings needed to be tightened to stop leaks;
-during filling operations, several pinhole-sized leaks developed in one of the glued corner joints at approximately 3 ft. elevation. Leaking began when the water elevation reached 7 ft. Atlantic Plastics patched the leaks on 9/27;
-bowing of side walls will be reduced by replacing angle bars with U-bars. Atlantic Plastics is to deliver U-bars during the week of 10/1;
-trial alum coagulation runs conducted on Chapel Hill raw water;
-kaolin, sodium bicarbonate, alum, fluoride recieved for feed water simulation, coagulation, and tracer study, respectively. Peat as source of organic material will be picked up during week of 10/1; bentonite re-ordered.

The work to be conducted during the next month is detailed on the following page. We are still awaiting the 1/4" polypropylene media.

[redacted]

Philip C. Singer
University of North Carolina

9/19/90 - BCM Flocculation Project

Experimental program for next 1-2 weeks:

1. Develop calibration curve for turbidity (NTU) versus mg/L of kaolinite, bentonite (montmorillonite), and peat. Make up stock suspensions of k, b, and p (1000 mg/L) and measure turbidity of various dilutions to determine weight corresponding to 5 NTU and 20 NTU of turbidity. Measure total organic carbon (TOC) concentrations of various dilutions of peat to determine weight corresponding to 2, 5, 10 mg/L TOC. (Use Beckmann 915B TOCAmaster.)

2. Conduct coagulation experiments using alum stock solution from OWASA to determine optimal alum dosage requirements for kaolinite and bentonite suspensions containing 5 and 20 NTU of turbidity and 168 mg/L $NaHCO_3$ (equivalent to 2x10-3 equiv/L or 100 mg/L alkalinity as $CaCO_3$). During alum addition, rapid mix at maximum setting for 1 minute, then mix at 60 rpm for 5 min, 30 rpm for 5 min, then 15 rpm for 5 min. Measure settled water turbidity after 5, 10, 20 min of settling. Measure pH of settled water.

Also conduct coagulation experiments as above for peat suspensions containing 2, 5, and 10 mg/L TOC and 168 mg/L $NaHCO_3$. Measure settled water turbidity and TOC after 5, 10, and 20 min of settling. Measure pH of settled water.

When these coagulation runs are completed, plot settled water turbidity and TOC as a function of alum dose for each of the three settling times, and for each of the three suspensions. When the runs are completed, we will analyze the data and decide on a suitable mixture of clay and peat for our simulated raw waters. We will then conduct one more set of coagulation experiments using these simulated mixtures for 5 and 20 NTU waters with various amounts of TOC.

3. Fill pilot tank with identical 1/2-in. polypropylene media on both sides. Fill to 3-ft depth. Run at 10 gpm and measure headloss at steady state. Conduct tracer study through both sides in parallel (see below). If both sets of results, i.e. headloss and residence time distribution (RTD) are the same, we can conclude that the two sides operate identically, and can proceed to fill one side with 3 ft of 1/4-in polypropylene media and conduct a set of steady-state clean water runs at 5, 10, 15 gpm through both sides in parallel, measuring steady-state headloss and RTDs at the three different flow rates.

4. For tracer study, I would suggest using fluoride as a step feed tracer. Get hydrofluosilicic acid from OWASA and make various dilutions; calculate F- concentration of

dilutions, and measure fluoride using a fluoride-selective electrode. (See appendix in Susan Teefy's 1989 MSEE report for procedures for step feed tracer analysis with fluoride.) The fluoride should be fed at the location where alum will be fed.

We should also do one tracer study with a dye in order to be able to visually see the flow pattern through the tank with the BCM in place (and to give Chris some pictures). This is best done via a pulse input of dye, using some food coloring as the tracer (either red or green). The dye is injected with a syringe (or added with a graduate cylinder, depending upon the volume of dye needed) at the inlet to the tanks, and effluent samples are analyzed colorimetrically from a standard curve prepared using a stock dilution of the dye. The key question before doing the dye tracer study is to determine how much dye to add in order to obtain measureable values in the effluent. The calibration curve should help answer this question.

5. After the residence time distributions and head loss data have been obtained for the two types of media and the different flow rates, we are ready to start feeding our simulated raw water and coagulant to the flocculator.

Monthly Progress Report / Buoyant Coarse Media Flocculator

October, 1990

The majority of the work done this month involved modifications to the pilot plant and performance of jar tests to determine the appropriate doses of kaolinite or bentonite, and peat to make up our simulated raw water and the requisite alum doses to coagulate the turbidity and TOC:

- Peat and bentonite for feed water simulation have been received.
- The tank developed a second leak below the original leak. Atlantic Plastics patched the leak on 10/19. The leak reappeared while filling the tank on 10/22. Additional glue was injected under the patch. No new leaks have been detected since that time.
- U-bars were delivered by Atlantic Plastics on 10/18 and have been installed.
- Guides for the tank dividers have been glued to the bottom of the tank to correct bending of dividers. Additional bars were added in the upper portion of the tank to correct bowing of tank walls and short circuiting in the tank.
- Method for sampling effluent was developed using sample ports and tubing at various depths. This method transports effluent at low velocity, preventing floc shearing.
- Jar tests were run for kaolite, bentonite, and peat solutions. Results are attached. Sufficient turbidity and TOC are attainable with a solution of just peat. Optimal results were provided with no pH adjustment and 20 mg of alum/l or pH adjusted to 6.5 and 15 mg of alum/l.
- Developed a curve for TOC/turbidity relationship for peat solutions.

As indicated above, we will use peat alone as our source of both 5 NTU and 5 mg/L TOC water. The feed will be at pH 7, containing 100 mg/L alkalinity as $CaCO_3$. Alum will be applied at a dose of 20 mg/L, with no pH adjustment. We expect that the modifications made to the pilot plant have made it leak-proof and that the tank dividers will fit securely in the tank. If this is the case, we will add the media and begin our tracer and headloss studies as detailed in last month's progress report.

Philip C. Singer
University of North Carolina

Coagulation of 5 NTU peat; pH adjusted to 6.5

DATE: October 23, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	RESIDUAL pH	RESIDUAL TURBIDITY 5	10	20	RESIDUAL TOC
1	5	6.60	5.00	4.20	4.50	5.29
2	10	6.55	2.30	1.20	0.90	1.99
3	15	6.50	2.70	2.00	0.95	1.99
4	20	6.45	2.70	1.80	1.15	1.93
5	25	6.35	5.10	2.70	1.55	1.84
6	0	6.70	5.10	4.70	4.20	3.15

Coagulation of 5 NTU peat; pH adjusted to 6.0

DATE: October 23, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	RESIDUAL pH	RESIDUAL TURBIDITY 5	10	20	RESIDUAL TOC
1	5	5.90	4.60	4.60	4.60	3.18
2	10	5.75	4.90	3.10	2.10	2.02
3	15	5.65	3.90	3.00	1.70	1.56
4	20	5.50	4.50	4.30	3.20	1.97
5	25	5.40	2.20	2.10	6.60	3.09
6	0	6.00	4.20	4.20	4.00	3.42

Coagulation of 5 NTU bentonite; pH adjusted to 6.5

DATE: October 23, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	RESIDUAL pH	RESIDUAL TURBIDITY 5	10	20	RESIDUAL TOC
1	5	6.70	3.70	2.20	1.04	
2	10	6.60	4.70	1.60	1.04	
3	15	6.55	6.20	2.60	1.59	
4	20	6.45	6.70	2.10	1.57	
5	25	6.35	6.40	3.40	1.45	
6	0	6.70	4.60	4.60	4.50	

Coagulation of 20 NTU bentonite; pH adjusted to 6.5

DATE: October 23, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	RESIDUAL pH	RESIDUAL TURBIDITY 5	10	20	RESIDUAL TOC
1	5	6.50	17.90	5.30	2.00	
2	10	6.40	13.00	3.40	1.41	
3	15	6.40	7.10	2.70	1.60	
4	20	6.30	6.80	2.50	1.51	
5	25	6.30	5.20	2.80	1.23	
6	0	6.60	16.40	16.30	15.70	

Coagulation of 5 NTU kaolite; pH adjusted to 6.5

DATE: October 16, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	RESIDUAL pH	RESIDUAL TURBIDITY 5	10	20	RESIDUAL TOC
1	5	6.40	3.90	3.70	3.40	
2	10	6.40	2.70	2.00	0.95	
3	15	6.35	3.10	1.90	0.97	
4	20	6.35	3.60	2.30	1.15	
5	25	6.30	3.50	2.40	1.30	
6	30	6.30	3.80	2.40	1.10	

Coagulation of 20 NTU kaolinite; pH adjusted to 6.5

DATE: October 16, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	RESIDUAL pH	RESIDUAL TURBIDITY 5	10	20	RESIDUAL TOC
1	5	6.35	10.10	8.60	7.80	
2	10	6.40	5.10	2.00	1.31	
3	15	6.15	6.20	2.70	0.90	
4	20	6.15	5.80	2.80	0.95	
5	25	6.10	4.20	3.40	1.34	
6	30	6.10	7.70	2.50	1.10	

Coagulation of 5 NTU kaolinite; pH unadjusted

DATE: October 16, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	RESIDUAL pH	RESIDUAL TURBIDITY 5	10	20	RESIDUAL TOC
1	5	7.45	2.30	2.30	2.20	
2	10	7.50	2.00	1.40	1.20	
3	15	7.50	3.60	2.40	1.10	
4	20	7.50	2.10	1.50	1.10	
5	25	7.45	3.10	1.90	0.98	
6	30	7.40	3.30	1.70	1.01	

Coagulation of 20 NTU kaolinite; pH unadjusted

DATE: October 16, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	RESIDUAL pH	RESIDUAL TURBIDITY 5	10	20	RESIDUAL TOC
1	5	7.50	5.10	5.00	4.90	
2	10	7.60	4.40	3.00	1.56	
3	15	7.55	8.90	4.00	1.60	
4	20	7.50	9.60	3.60	1.57	
5	25	7.45	10.20	6.10	2.20	
6	30	7.40	9.90	4.30	1.72	

Coagulation of 5 NTU peat; pH unadjusted

DATE: October 16, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	RESIDUAL pH	RESIDUAL TURBIDITY 5	10	20	RESIDUAL TOC
1	5	7.75	4.20	4.10	3.70	7.35
2	10	7.60	4.70	4.30	4.20	6.23
3	15	7.60	4.40	3.40	2.50	5.11
4	20	7.60	3.00	1.20	0.70	3.04
5	25	7.50	3.00	1.80	0.67	3.07
6	30	7.50	3.40	1.30	0.93	2.67

Coagulation of 5 NTU peat; pH adjusted to 6.5

DATE: October 16, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	RESIDUAL pH	RESIDUAL TURBIDITY 5	10	20	RESIDUAL TOC
1	5	6.40	5.00	4.60	4.60	4.77
2	10	6.25	3.50	2.10	1.70	2.60
3	15	6.25	3.40	1.40	0.95	2.03
4	20	6.20	3.60	1.80	0.99	1.93
5	25	6.15	4.60	2.40	1.23	2.26
6	30	6.05	5.60	3.00	1.45	2.01

Monthly Progress Report / Buoyant Coarse Media Flocculator

November 1990

This month, we made our final adjustments to the design of the tank to correct for operational problems, and our first set of flocculation runs. Both sides of the tank were filled with 2 1/2 feet of 1/2-inch polypropylene spheres in order to verify the uniformity of the two parallel chambers. Dye test tracer studies and headloss measurements were made, along with one flocculation run. The tests and observations are reported below as bullets:

- The flow meters were calibrated by making measurements of volume delivered over a timed period. The results were found to be reproducible after the valves were moved from the upstream side of the meters to the downstream side.

- Tracer studies were run with methylene blue at flow rates of 5 and 10 gpm. Both columns contained 2 1/2 feet of 1/2-inch polypropylene spheres. The tracer curves are attached. Both sides gave consistent and parallel results, verifying that flow through both sides was essentially identical. The median residence time through the 2 1/2 feet of media was 63 seconds at 10 gpm and about 120 seconds at 5 gpm, consistent with the theoretical residence times at these flow rates. Because of the short residence time, it was not feasible to conduct a tracer study at 15 gpm.

- Headloss was measured through both columns at 5, 10, 15, 20, and 30 gpm flow rates. The headloss curves are attached. Again, the two parallel columns gave essentially identical results. The maximum headloss developed was 4 mm at the 30 gpm flow rate.

- A flocculation run was conducted through the two parallel beds of 1/2-inch media at a flow rate of 10 gpm. The feed water was our peat suspension, having a turbidity of 5 NTU and a TOC concentration of 5 mg/L. The alum dose was 20 mg/L, producing a pH of 7.0 in the treated water. The results are shown in the attached table. The effluent turbidity measured immediately below the media showed a small reduction in turbidity across the bed, indicating that some of the floc were being trapped in the bed. A corresponding increase in headloss could not be detected; the measured headloss was only about 6 mm at this flow rate. The settled water turbidity (20 min of settling) of the samples taken immediately below the bed showed essentially no reduction in turbidity compared to the samples measured immediately, i.e. no settleable particles were produced as a result of passage through the media.

  After 40 min of run time at 10 gpm, the flow rate was reduced to 5 gpm to determine if the additional residence time would improve flocculation. Only a small improvement was noted.

In order to verify that the alum dose was sufficient to destabilize the particles, samples were taken from below the bed and placed on the jar test apparatus and subjected to mechanical flocculation. The turbidity of the settled water following mechanical flocculation was 2.2 NTU, indicating that the poor performance of the BCM flocculator was not attributable to improper coagulant feed.

- Additional jar tests were conducted for 5 and 20 NTU of kaolinite at various pH values, with no addition of coagulant. The objective of these tests was to adjust the pH of the suspensions to the zero point of charge of the kaolinite so that the clay could be neutralized without the addition of an external coagulant. The results are attached. No significant flocculation was observed.

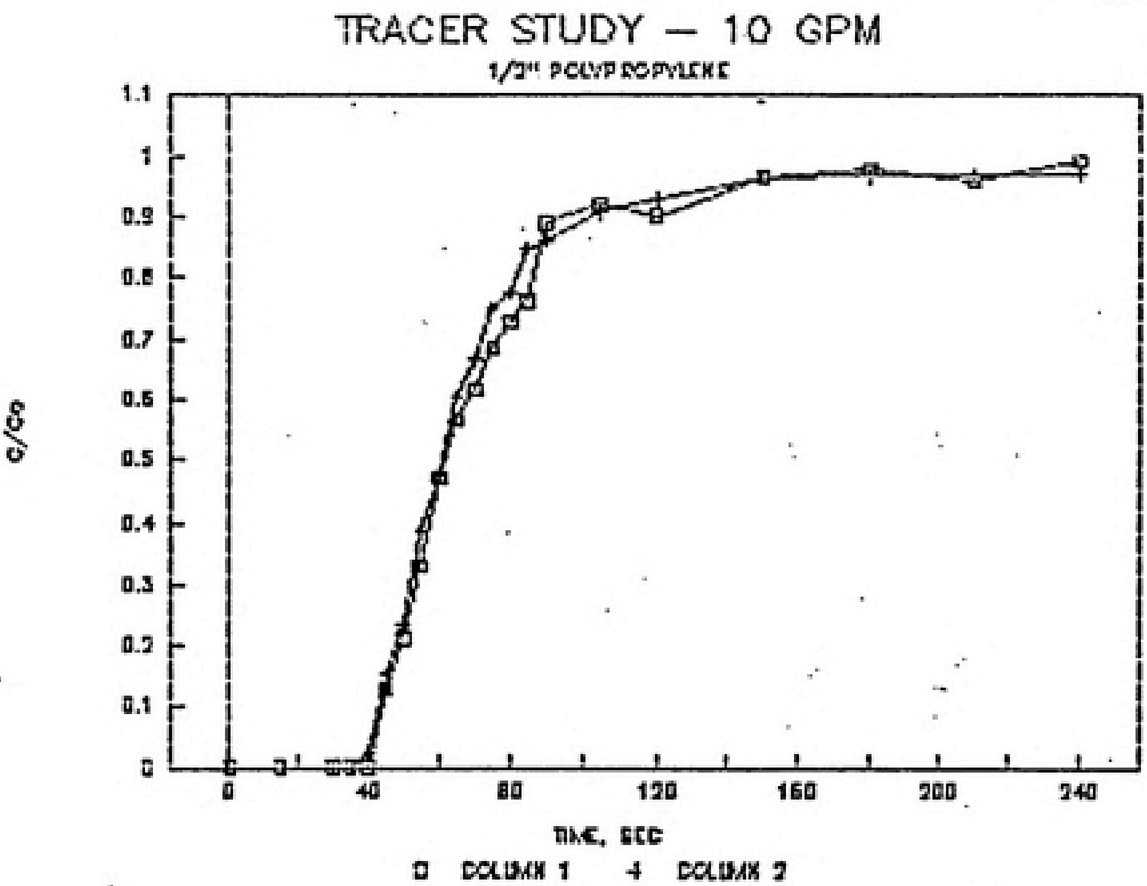
Plans for next month:

- Load two sides of pilot plant with 1/4-inch and 1/2-inch polypropylene spherical media, to a depth of 5 feet. Determine headloss and residence time characteristics at 5, 10, 15 gpm and run flocculation experiments. Consider running with irregularly-shaped media to increase headloss.

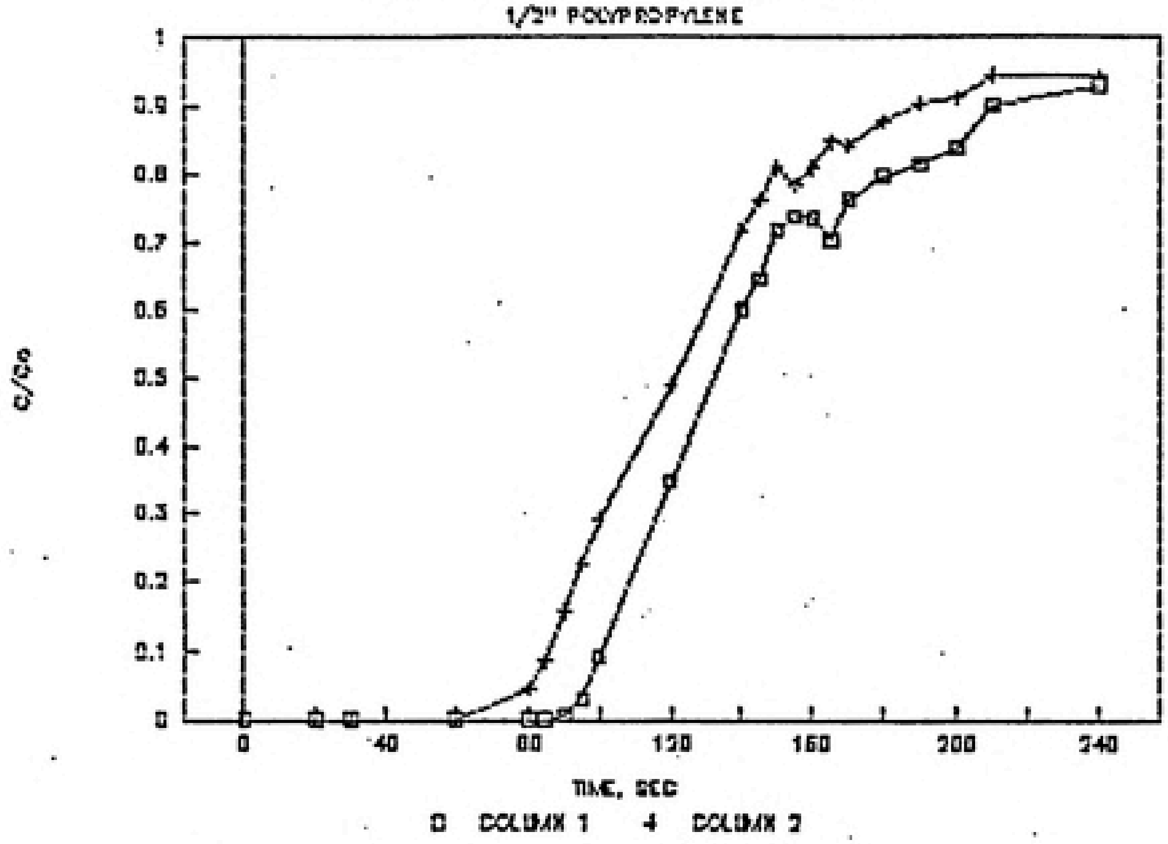
- Consider running with kaolinite in the feed water in place of peat, using alum as the coagulant. Use higher concentrations of kaolinite (20 NTU) to enhance contact opportunities for flocculation in the bed.

- Conduct jar tests using polymer in addition to alum in order to increase the floc strength of the coagulated particles making them more resistant to shearing forces in the bed.

Philip C. Singer
University of North Carolina


TRACER STUDY — 10 GPM
1/2" POLYPROPYLENE
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
c/co
0
40
80
120
160
200
240
TIME, SEC
□ COLUMN 1 + COLUMN 2

TRACER STUDY — 5 GPM



COAGULATION RUN #1, 11/20/90

FEED WATER CHARACTERISTICS: 5 NTU TURBIDITY, 5 mg/l TOC
PEAT - pH 8.05, PEAT+ALUM - pH 7
COAGULANT DOSAGE: 20 mg/l ALUM

COLUMN 1, 2 1/2 FEET OF 1/2" POLYPROPYLENE:

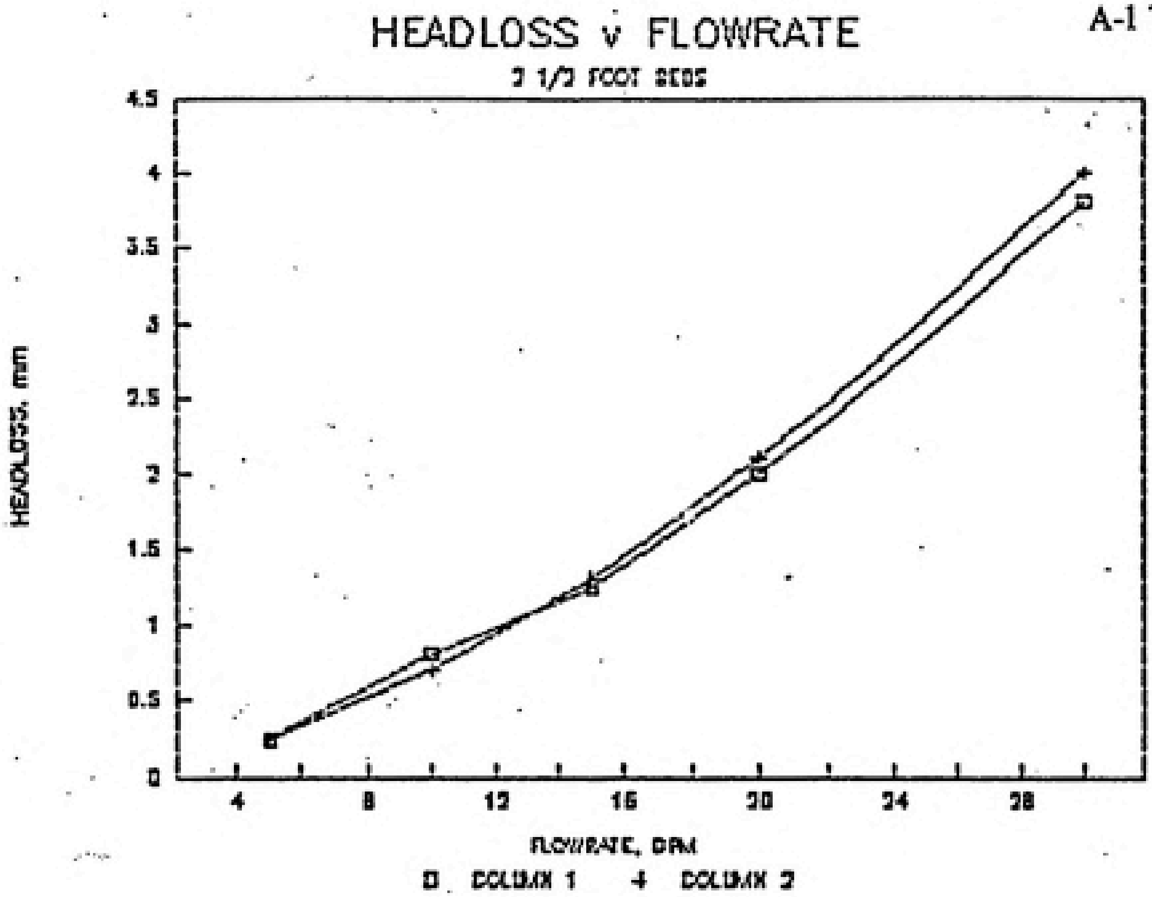
SAMPLE	FLOWRATE	TIME	HEADLOSS	TURBIDITY, NTU			pH
	GPM	MIN	mm	INFLUENT	EFFLUENT	SETTLED	
1	10	0	6.00	5.60	5.90	5.40	8.00
2	10	15	5.00	8.00	7.60	7.40	7.10
3	10	40	5.00	9.00	7.30	7.40	7.10
4	5	85		7.40	6.80	6.30	7.10

COLUMN 2, 2 1/2 FEET OF 1/2" POLYPROPYLENE:

SAMPLE	FLOWRATE	TIME	HEADLOSS	TURBIDITY, NTU			pH
	GPM	MIN	mm	INFLUENT	EFFLUENT	SETTLED	
1	10	0	5.50	5.60	5.70	5.40	8.00
2	10	15	6.00	8.00	7.60	7.50	7.10
3	10	40	6.00	9.00	7.40	7.50	7.10
4	5	85		7.40	6.70	6.40	7.10

After 40 minutes of run time at 10 GPM (3 samples), cut flow rate to 5 GPM to determine if addition residence time would improve flocculation. A small improvement was noted.

Mixed two samples with jar test apparatus after they had settled for 20 minutes. The resulting turbidities were as follows:
Sample 1 4.4 NTU
Sample 2 2.2 NTU
This indicates that coagulant dosage was sufficient for flocculation.


HEADLOSS v FLOWRATE
2 1/2 FOOT BEDS
HEADLOSS, mm
FLOWRATE, GPM
COLUMN 1
COLUMN 2

Flocculation of 5 NTU kaolinite; effect of pH only
(no coagulant added)

DATE: November 13, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	HNO3 DOSAGE mg/l	INITIAL pH	RESIDUAL pH	RESIDUAL TURBIDITY 5	20
1	0.00	0.72	6.00	6.45	3.90	3.70
2	0.00	1.05	5.00	5.30	3.80	3.70
3	0.00	1.10	4.50	4.65	3.70	3.50
4	0.00	1.15	4.00	4.10	3.50	3.50
5	0.00	1.45	3.50	3.60	3.40	3.90
6	0.00	0.00	7.40	7.40	3.60	3.60

Flocculation of 20 NTU kaolinite; effect of pH only
(no coagulant added)

DATE: November 13, 1990

SAMPLE NUMBER	ALUM DOSAGE mg/l	HNO3 DOSAGE mg/l	INITIAL pH	RESIDUAL pH	RESIDUAL TURBIDITY 5	20
1	0.00	0.70	6.00	6.20	17.00	16.00
2	0.00	1.00	5.00	5.15	16.00	14.00
3	0.00	1.05	4.50	4.60	16.00	17.00
4	0.00	1.10	4.00	4.15	16.00	16.00
5	0.00	1.45	3.50	3.60	18.00	15.00
6	0.00	0.00	7.40	7.45	15.00	17.00

Monthly Progress Report / Buoyant Coarse Media Flocculator

December 1990

This month, we completed several sets of pilot-scale runs to determine clean bed head losses and residence time distributions for a variety of media at several different flow rates. The head loss measurements were used to calculate G-values. Several flocculation runs were made with kaolinite, at feed water turbidities of 20 and 200 NTU, using alum and polymer as coagulants. The results are presented below as bullets, with supporting data attached.

-The two sides of the flocculator were loaded with four and a half to five and a half feet of 1/4-inch and 1/2-inch polypropylene spheres, 1/2-inch spherical and the irregular (approx. 3/8-inch) 3M ceramic media, and the 1/2-inch and 3/4-inch Norpak media. Clean bed head losses, in mm/ft, measured at flow rates of 5 to 30 gpm are shown in Figures 1A to 3A.

-The corresponding G-values calculated for 5-ft bed depths of the various media at the different flow rates tested are illustrated in Figures 1B to 3B. The G-values were calculated using the equation shown in Table 1. The G-values for the Norpak media are relatively low compared to the polypropylene and ceramic media; flow rates in excess of 20 gpm are required to achieve G-values of at least 20 sec-1. The 3/8-inch, irregular ceramic media and the 1/4-inch polypropylene spheres produce G-values of about 50 sec-1 at flow rates of about 8 to 10 gpm.

-Pulse-input tracer studies were conducted at flow rates of 5 to 15 gpm for the 1/2-inch spherical and irregular 3M media and the 3/8-inch and 3/4-inch Norpak. Illustrative results are shown in Figures 4 to 7. The mean residence times are seen to be relatively close to the theoretical residence times; the small difference is probably a result of the additional residence time in the inlet pipe to the bed.

-Numerous jar tests were conducted to determine and verify the optimal coagulant doses for kaolinite at initial turbidities of 20 and 200 NTU. Alum alone and alum in combination with polymer were tested, the latter to provide increased floc strength. The jar tests had to be conducted regularly because the temperature of the feed water (Chapel Hill tap water) decreased significantly during this month, from about 20 C to 11 C. For 20 NTU of kaolinite, the optimal alum dose was found to be about 15 mg/L at 20 C, yielding a settled water turbidity (after 20 min of settling) of about 2 NTU. At 11 C, the optimal dose of alum was 20 mg/L, but the settled water turbidity was only 5 NTU. Increasing the rapid mixing time for alum at the colder water temperature from 1 to 2 minutes, or the addition of 0.3 to 0.5 mg/L of polymer (Betz 1160P) in combination with alum produced settled water turbidities of less than 2 NTU. For 200 NTU of kaolinite, the optimal dose of alum was 25 mg/L, producing settled water turbidities of about 4 NTU. Illustrative jar test results are shown in Tables 2 to 4. The optimal doses of 25 mg/L alum and 0.5 mg/L polymer for 20 NTU of kaolinite were selected for the BCM flocculator studies during cold temperature operation.

-Modifications to the chemical feed system for the BCM flocculator were made to allow for the feeding and mixing of both the alum and polymer. Alum was fed prior to the 1-inch PVC pipe, giving a Reynold's number of 24,000 at 10 gpm. The polymer was applied prior to two 90-degree bends in the feed line, after which the chemically-treated water passed through a 1 1/2-inch KOFLO static mixer. Two 1 1/2-inch mixers were inserted in the vertical feed lines to each of the two sides of the flocculator, ahead of the flow meters. The feed arrangement is illustrated in Figure 8. Samples taken from the influent to the two columns were placed on the jar test apparatus and subjected to tapered mechanical flocculation to verify that the chemical doses and mixing conditions were able to satisfactorily destabilize the kaolinite particles. Settled water turbidities of less than 2 NTU were produced.

-The two columns were loaded with 5.5 feet of the 1/2-inch 3M spherical media and 5.75 feet of the 1/4-inch polypropylene spheres. The feed water contained 20 NTU of kaolinite, and the chemical doses were 25 mg/L alum and 0.5 mg/L polymer. The temperature was 11.5 C, the pH was 7.0, and the flow rate was 10 gpm. For the 1/2-inch 3M media, the head loss increased from 30 to 60 mm over the course of the first 5 hours, corresponding to G-values of 50 to 70 sec-1. The effluent turbidity from the column averaged about 10.2 NTU. No significant trend in effluent turbidity was observed over the 5-hour observation period, and no visible floc were observed. The effluent was allowed to settle for 20 minutes, but no appreciable settling took place. Column operation was started up again the next day, and the flocculator ran for an additional 4 hours. No improvement in performance was noted.

For the 1/4-inch polypropylene bed, the head loss increased from 50 to 120 mm over the first 5 hours of operation, corresponding to G-values of 67 to 102 sec-1. The turbidity was reduced from 20 NTU in the feed to as low as 5.0 NTU in the column effluent. No settleable floc were observed in the effluent. (The effluent turbidity after 20 min of settling was essentially the same as the effluent turbidity itself.) In contrast, mechanical flocculation of the feed water produced settled water turbidities of about 2 NTU after 20 min of settling. The feed water turbidity was increased to 200 NTU for 2 hours to increase the rate of head loss accumulation.

The following day, the ripened 1/4-inch PP column was operated at 10 gpm with a kaolinite feed of 20 NTU. The head loss continued to increase from 155 to 170 mm (G = 122 sec-1) over 4 hours. The effluent turbidity averaged about 13 NTU, but settleable floc were clearly visible. The settled water turbidity of the column effluent, after 20 min of settling, averaged about 5.5 NTU. This represents the most successful flocculation run to date.

The results of these two runs are presented in Tables 5 and 6.

Plans for Next Month:

The preceding run suggests that a head loss approaching 150 mm (corresponding to a G-value of about 115 sec-1) must be obtained in order to achieve flocculation in the column. Accordingly, we will focus our activities on the 1/4-inch PP and 3/8-inch irregular 3M media. Extended runs will be made to reach steady-state operation at flow rates of 5 up to 15 gpm. Kaolinite feeds of 200 NTU will be applied initially in order to hasten ripening of the bed. In view of the importance of water chemistry and temperature, jar tests will be run regularly in order to verify that the coagulant doses are appropriate. Some tests with ferric chloride will be conducted as it is suggested that this coagulant produces stronger floc than alum and is more effective at cold water temperatures.

Philip C. Singer
University of North Carolina

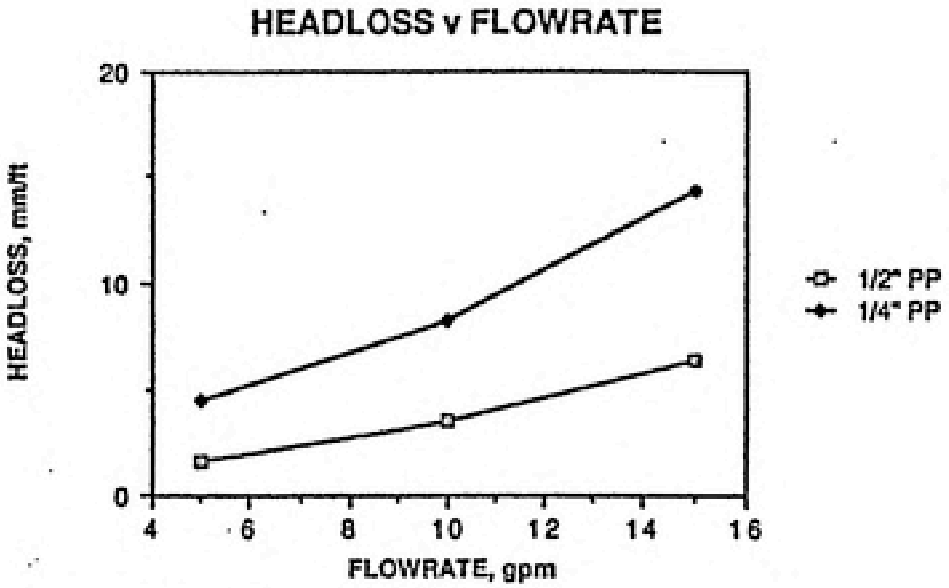

HEADLOSS v FLOWRATE
HEADLOSS, mm/ft
FLOWRATE, gpm
1/2" PP
1/4" PP
0
10
20
4
6
8
10
12
14
16

FIG. 1A

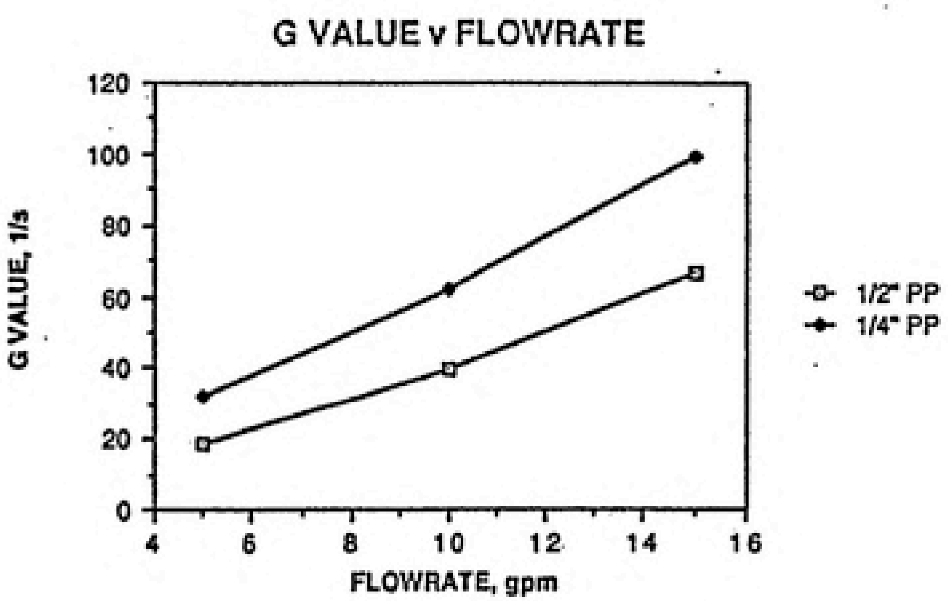

G VALUE v FLOWRATE
G VALUE, 1/s
FLOWRATE, gpm
1/2" PP
1/4" PP
0
20
40
60
80
100
120
4
6
8
10
12
14
16

FIG. 1B

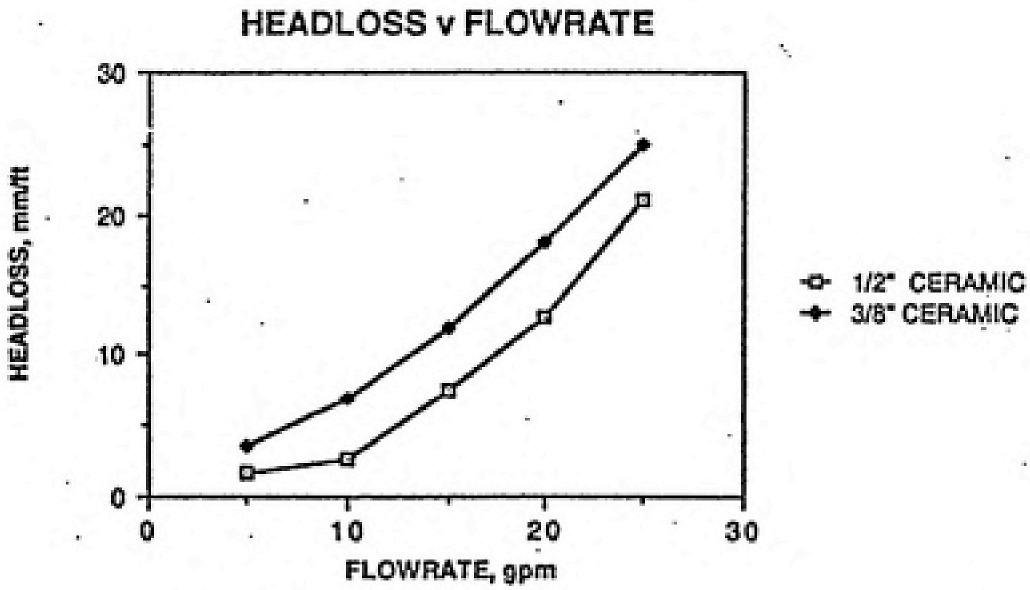

HEADLOSS v FLOWRATE
HEADLOSS, mm/ft
FLOWRATE, gpm
0
10
20
30
1/2" CERAMIC
3/8" CERAMIC

FIG. 2A

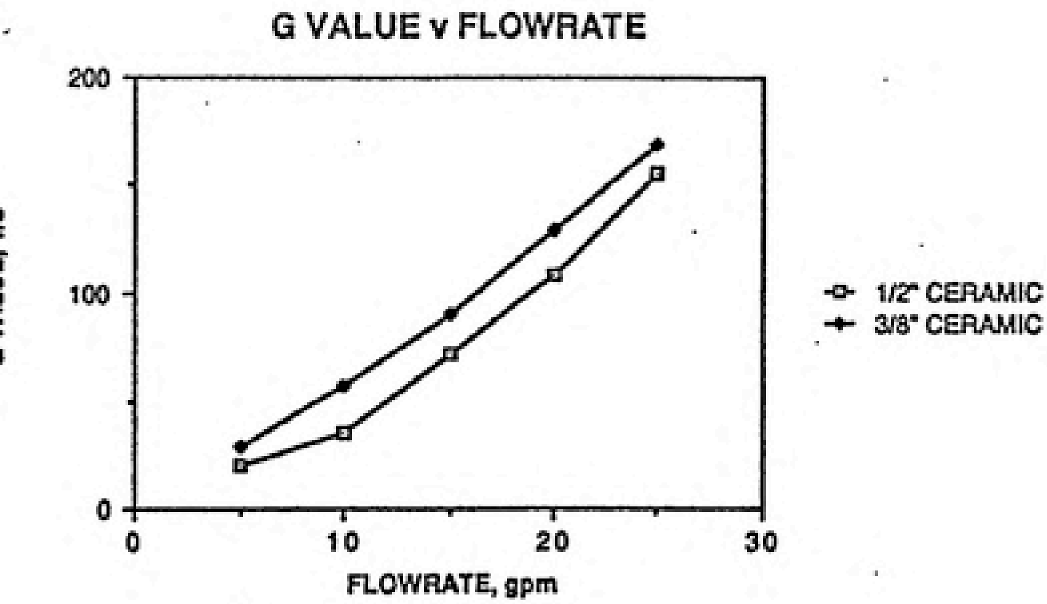

G VALUE v FLOWRATE
G VALUE, 1/s
FLOWRATE, gpm
0
100
200
10
20
30
1/2" CERAMIC
3/8" CERAMIC

FIG. 2B.

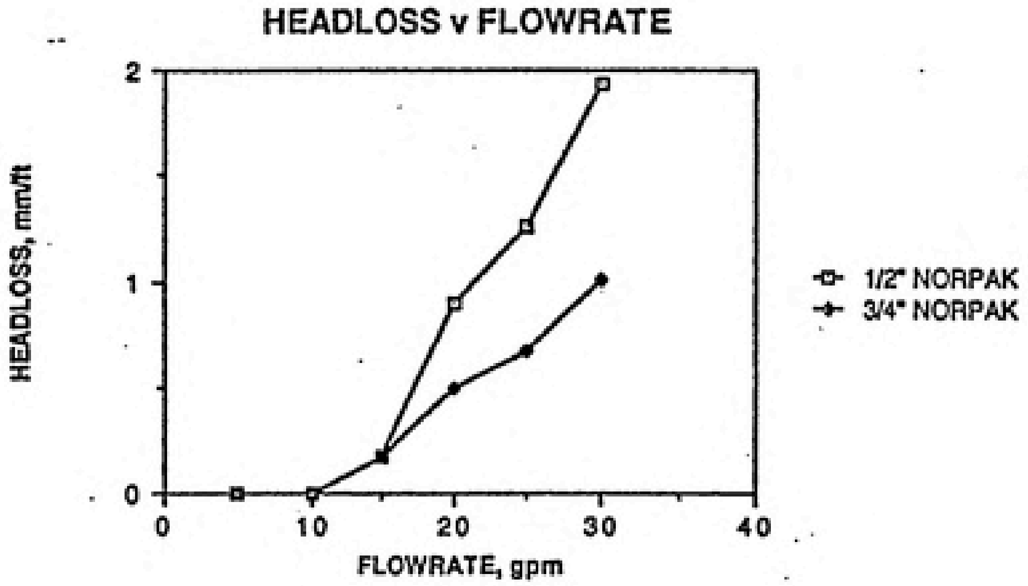

HEADLOSS v FLOWRATE
HEADLOSS, mm/ft
FLOWRATE, gpm
0
1
2
0
10
20
30
40
1/2" NORPAK
3/4" NORPAK

FIG. 3A

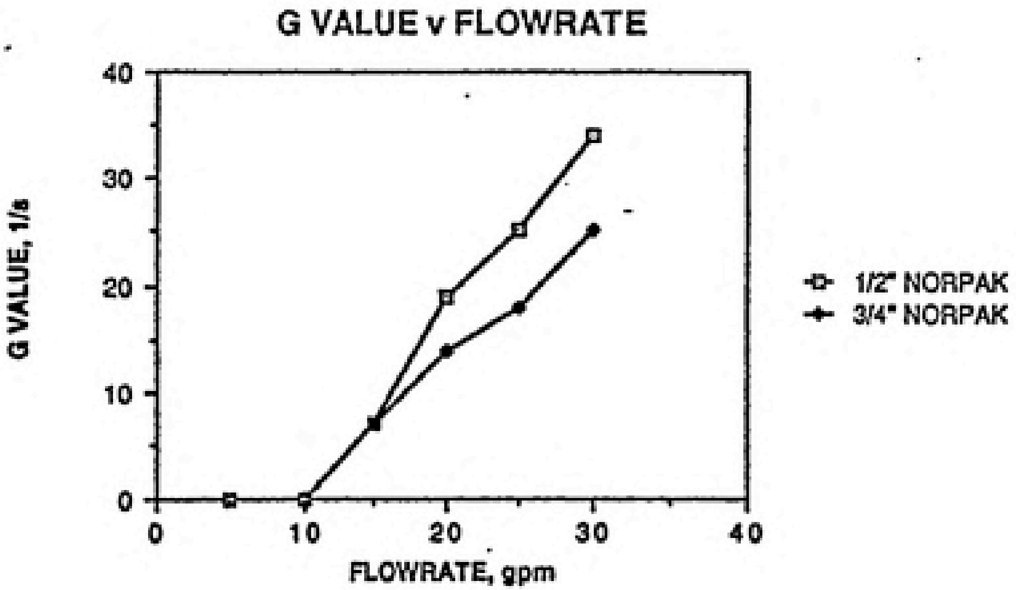

G VALUE v FLOWRATE
G VALUE, 1/s
FLOWRATE, gpm
0
10
20
30
40
0
10
20
30
40
1/2" NORPAK
3/4" NORPAK

FIG. 3B.

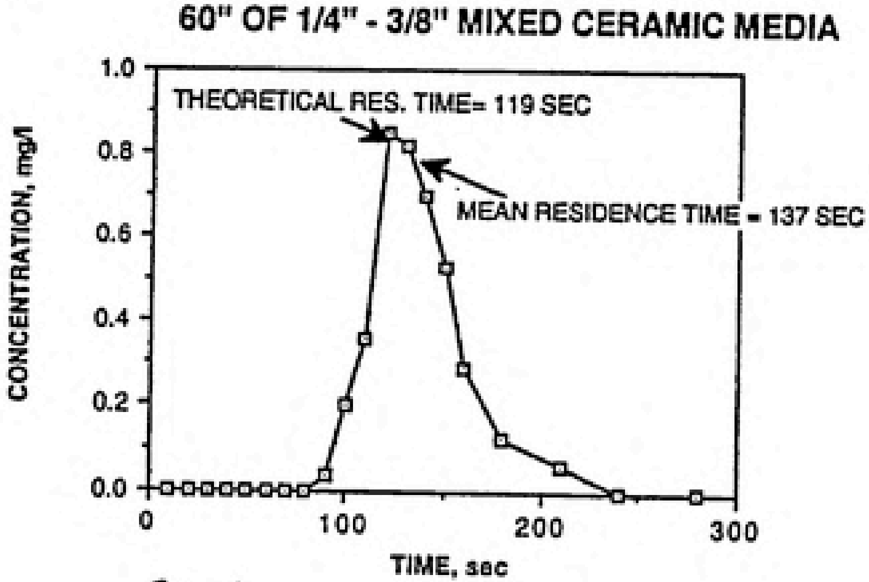

60" OF 1/4" - 3/8" MIXED CERAMIC MEDIA
THEORETICAL RES. TIME= 119 SEC
MEAN RESIDENCE TIME = 137 SEC
CONCENTRATION, mg/l
TIME, sec
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300

FIG. 4

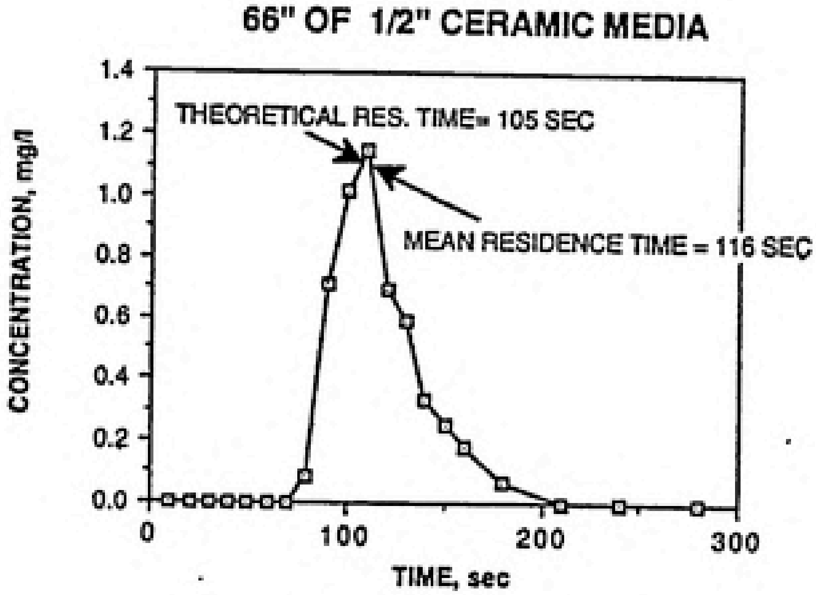

66" OF 1/2" CERAMIC MEDIA
THEORETICAL RES. TIME= 105 SEC
MEAN RESIDENCE TIME = 116 SEC
CONCENTRATION, mg/l
TIME, sec
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300

FIG. 5

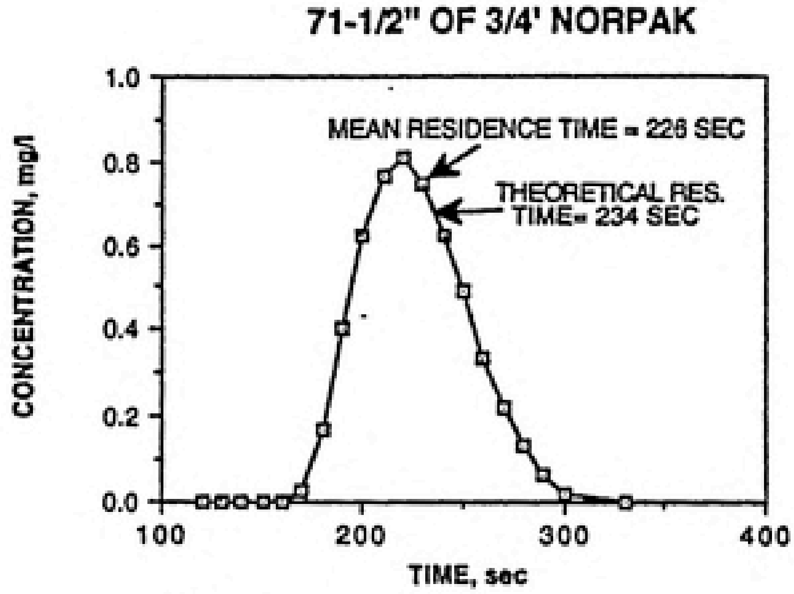

71-1/2" OF 3/4' NORPAK
MEAN RESIDENCE TIME = 226 SEC
THEORETICAL RES. TIME= 234 SEC
CONCENTRATION, mg/l
1.0
0.8
0.6
0.4
0.2
0.0
100
200
300
400
TIME, sec

FIG. 6

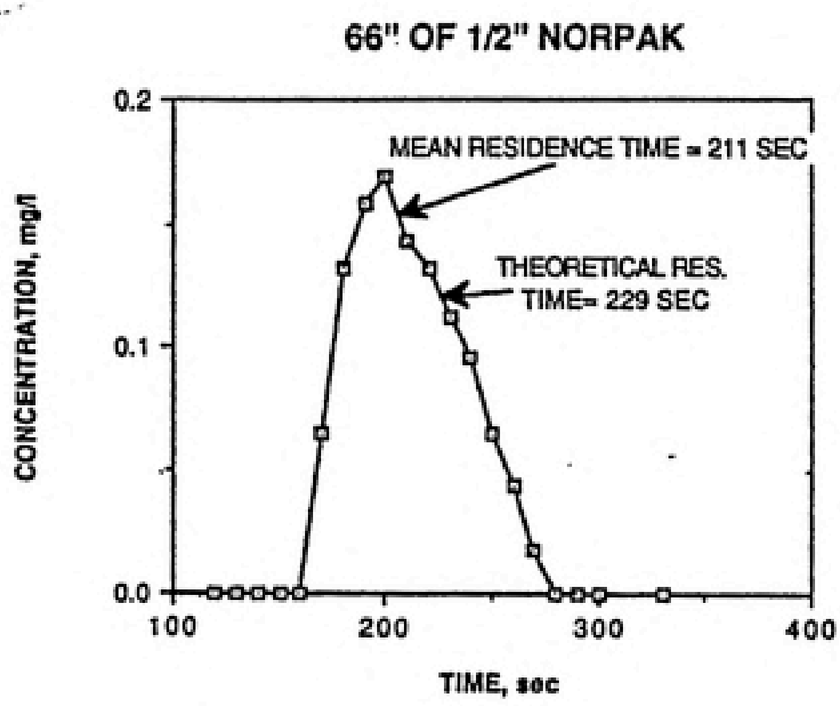

66" OF 1/2" NORPAK
MEAN RESIDENCE TIME = 211 SEC
THEORETICAL RES. TIME= 229 SEC
CONCENTRATION, mg/l
0.2
0.1
0.0
100
200
300
400
TIME, sec

FIG. 7

TABLE 2

Temperature Effects on Flocculation Date: 12/11/9(

Water: Tap water from outside tanks
Temp.: 11.5 C
Coagulant: Al2(SO4)3*14H2O
Turbidity: 20 NTU as Kaolinite
Alkalinity: NaHCO3 84 mg/l

Jar	1	2	3	4	5	6
Parameter						
alum/mg/l	10	15	20	25	30	0
Init. pH	7.30	7.30	7.25	7.30	7.30	7.25
Init.Turb with alum	20	20	23	21	19	20
removal						
5 min	20	17.5	14.4	19.5	17.8	20
20 min	15.8	8.2	4.9	5.5	5.1	19
removal/%	21.0	59.0	78.7	73.8	3.2	5.0
pH	7.10	7.00	7.00	6.90	.80	7.10

Jartest with temperature adjusted water

Water: Tap water , temperature adjusted
Temp.: 20 C
Coagulant: Al2(SO4)3*14H2O
Turbidity: 20 NTU as Kaolinite
Alkalinity: NaHCO3 84 mg/l
pH adjusted: 7.25

Jar	1	2	3	4	5	6
Parameter						
alum/mg/l	10	15	20	25	30	0
Init. pH	7.3	7.25	7.2	7.2	7.2	7.3
Init.Turb with alum	23	20	21	24	20	23
removal						
5 min	10.1	8.4	7	9	6.4	21
20 min	4.6	2	1.7	1.7	1.9	20
removal/%	80.0	90.0	91.9	92.9	90.5	13.0
pH	7.1	7.0	7.0	6.9	6.9	7.2

Remarks

Comparison shows significant better removal at higher temperature.
Suggestions to compensate these effects without increasing temperature: Addition of polymer
Stronger coagulant (Ferric Chloride)

TABLE 3.

Jartest Date: 12/15/90

This is to check the influence of different rapid mix times on coagulation.

Water:	Tap water from outside tanks		
Temp.:	11.0 C		
Coagulant:	$Al2(SO4)3*14H2O$ (three month old)		
Turbidity:	20 NTU	as Kaolinite	
Alkalinity: NaHCO3	42 mg/l	additional	

Jar	1	2	3	4	5	6
Parameter						
alum/mg/l	25.0	25.0	25.0	25.0	25.0	25.0
Poly/mg/l	0.3	0.5	0.3	0.5	0.3	0.5
Init. pH	7.3	7.5	7.4	7.5	7.5	7.6
Init.Turb	18.7	18.5	18.5	18.0	19.2	18.0
with alum						
removal						
5 min	2.2	2.5	1.6	2.2	2.0	1.4
20 min	1.6	1.4	1.2	1.2	1.2	1.0
50 min	1.1	1.1	1.0	0.9	1.1	0.9
removal/%	94.1	94.1	94.6	95.0	94.3	95.0
pH						

Remarks

* pH after sedimentation not measured
* Mixing regime:
  Jars 1 and 2 - 1 minute with alum and polymer
  Jars 3 and 4 - 1 minute with alum, then add polymer and mix an additional minute
  Jars 5 and 6 - 2 minutes with alum and polymer
* Jars 1&2 showed significant slower aggregation
* Jars 4&6 showed heavy flocs and sedimentation
  after 6 minutes mixing (5 minutes at 60 RPM and 1 minutes at 30 RPMs)

TABLE 4.

Effects of Initial Turbidity on Flocculation   Date: 12/11/90

Compare with first jartest from 12/11/90 (Temperature effects)

Water:	Tap water from outside tanks
Temp.:	12.5 C
Coagulant:	Al2(SO4)3*14H2O (three month old)
Turbidity:	200 NTU as Kaolinite
Alkalinity: NaHCO3	84 mg/l

Jar	1	2	3	4	5	6
Parameter						
alum/mg/l	20	25	30	35	40	0
Init. pH	8.1		8.2			8.1
Init.Turb with alum	180	189	187	186	180	174
removal						
5 min	24	20	14	11	19	150
20 min	5.8	3.9	3.9	3.2	3.6	160
removal/%	96.8	97.9	97.9	98.3	98.0	8.0
pH	7.4	7.2	7.2	7.1	7.0	8.0

Remarks

Due to the high tubidity there was sedimentation in sample flasks and therefore no steady turbidity measurement possible. Values in high ranges vary +- 10 NTU!

TABLE 5.

12/19/90.doc/wk1

COAGULATION RUN #4-1 12/18/90 12/18/90

FEED WATER CHARACTERISTICS:

Turbidity:	19..22	NTU
Coagulant: Al2(SO4)3*14H2O	25	mg/l
Polymer:	0.5	mg/l
Alkalinity: NaHCO3	62	mg/l
Raw water pH		
Raw water pH (with alum)	7.0..7.2	
Temperature:	11.5	C

Column I

Media: 1/2 " 3M B.-Height 5.5 feet

SAMPLE #	FLOWRATE GPM	TIME min	HEADLOSS mm	G-VALUE 1/s	TURBIDITY EFFLUENT	SETTLED	FEED SETTLED
1	10	0	30	51.6	11.3	11.2	2.3
2	10	30	31	52.5	10.7	10.6	
3	10	0	31	52.5			
4	10	15	39	58.8	10.6	10.5	
5	10	45	40	59.6	10.2	10.1	
6	10	90	39	58.8	10.3	9.2	2.0
7	10	150	50	66.6	10.4	10.1	
8	10	210	57	70.9	10.0	9.5	1.2
9	10	270	59	72.3	10.3	9.3	
10	10	0	58	71.6	12.0	11.8	2.2
11	10	30	58	71.6	13.0	12.5	1.3
12	10	90	60	73.0	13.0	11.9	
13	10	120	51	67.4	12.3	12.2	0.4
14	10	150	58	71.6	12.4	11.7	0.5
15	10	230	69	78.2	12.1	11.3	

Remarks

* Between sample# 2 and 3 plant was shut down to conduct repairs on leaking polymer feed pump. Pumphead was exchanged to release pressure' forces.
* Between 9 and 10 column was shut down again to focus on coagulation in column II. Run was continued on 12/19/90.
* Between 13 and 14 additional static inline mixer were inserted to enhance performance (see also jartest and mixing time).

TABLE 6

Column II

Media: 1/4 " PP B.-Height 5.75 feet

SAMPLE #	FLOWRATE GPM	TIME min	HEADLOSS mm	G-VALUE 1/s	TURBIDITY EFFLUENT	SETTLED	FEED SETTLED
1	10	0	51	67.4	8.1	11.2	2.3
2	10	30	58	71.6	7.7	10.6	
3	10	0	69	78.2			
4	10	15	72	79.4	6.5	6.0	
5	10	45	77	82.5	6.3	5.6	
6	10	90	79	83.7	5.3	4.9	2.0
7	10	150	100	93.7	5.6	5.5	
8	10	210	110	98.3	5.8	5.0	1.2
9	10	270	120	102.7	5.8	5.1	
10	10	330	139	110.6	32.0	18.0	5.2
11	10	390	140	111.0	32.0	21.0	
12	10	0	155	117.1	15.0	9.1	2.2
13	10	30	157	117.5	15.0	6.4	1.3
14	10	60	159	118.3			
15	10	90	164	120.4	12.0	5.4	
16	10	120	140	111.0	12.2	5.1	0.4
17	10	150	152	115.8	13.4	6	0.5
18	10	230	168	121.6	14	5.8	

Remarks

* Between sample# 2 and 3 plant was shut down to conduct repairs on leaking polymer feed pump. Pumphead was exchanged to release pressure forces.
* From 9 to 11 clay dosage was increased to accelerate the clogging of the bed. Then column was shut down and run continued on 12/19/90. (samples 12 to 18)
* Between 15 and 16 additional static inline mixer were inserted to enhance performance (see also jartest and mixing time).

Philip C. Singer
Professor and Director
Water Resources Engineering Program

Monthly Progress Report / Buoyant Coarse Media Flocculator

January 1991

This month, we made four pilot-scale flocculation runs at turbidities of 20 and 200 NTU of kaolinite, at flow rates of 5, 7, 10, and 15 gpm. Alum (with polymer) and ferric chloride were used as coagulants. Several jar tests were also performed to test the effects of temperature, polymer dosage, initial turbidity, and ferric chloride dosage on flocculation effectiveness. The results are presented below as bullets, with supporting data attached. These are the same results we discussed during your visit to UNC with Hollie Scott on January 31.

- Jar tests were conducted to determine the optimal ferric chloride dose for 200 NTU of turbidity. A 10 mg/L dosage produced a settled water turbidity of 1.2 NTU. Alum/polymer combinations were also tested for 200 NTU of kaolinite. The optimal combination was found to be 25 mg/L alum and 0.1 mg/L of polymer, producing a settled water turbidity of 2.3 NTU. Larger and more rapidly-settling floc were produced with the ferric chloride compared to alum.

- Temperature effects were examined for a 20 NTU water dosed with 25 mg/L alum and 0.5 mg/L polymer. Temperature was varied from 6.1 to 12.7 C using combinations of water from the outside storage tank and hot tap water. As expected, 20-minute settled water turbidity improved as water temperature increased. Water temperature will be a significant factor in our flocculation runs, particularly during the winter, and we will need to conduct jar tests on a routine basis to insure that the chemical doses are appropriate for effective coagulation.

- On January 9, continuous-flow pilot-scale flocculation experiments were initiated to compare 5.7 feet of 1/4-inch polypropylene media to 5 feet of mixed ceramic media. Operating conditions were 10 gpm flow rate, 20 to 200 NTU of influent turbidity, 25 mg/L alum and 0.1-0.2 mg/L polymer. The run lasted for 9 hours. The results for the two media were similar for headloss and settled water turbidity of the effluent. Headlosses up to 110 mm were achieved, corresponding to G-values of about 90-95 sec-1. Effluent turbidities as low as 12 NTU were achieved, but after settling, the residual turbidity was about 10 NTU. It was decided to concentrate our efforts on the ceramic media because it is less expensive than the polypropylene media.

- Beginning on January 15, the mixed ceramic media was tested at flow rates of 10 and 7 gpm, influent turbidities ranging from 19-27 NTU, 25 mg/L alum, and 0.3 mg/L polymer. At 10 gpm, headlosses up to 214 mm were developed; settled water turbidity averaged about 11 NTU. At 7 gpm, headlosses up to 211 mm were developed, with settled water turbidities averaging 8.5 NTU. The run lasted for about 35 hours.

- Beginning on January 23, the same ceramic media was evaluated at flow rates of 5 and 15 gpm, influent turbidities ranging from 16-23 NTU, 25 mg/L alum, and 0.3 mg/L polymer. At 5 gpm, headlosses up to 183 mm were developed; settled water turbidity averaged 7.2 NTU. At 15 gpm, headlosses reached 347 mm, producing an average settled water turbidity of 10.2 NTU. The run lasted for 22 hours.

- On January 31 and February 1, the ceramic media was tested under similar conditions, but using ferric chloride as the coagulant in place of alum. Operating conditions were 5 and 10 gpm flow rates, influent turbidity of 20 NTU, and 11 mg/L ferric chloride. No polymer was used. At 10 gpm, headlosses up to 286 mm were developed, producing an average settled water turbidity of 9.1 NTU. At 5 gpm, headlosses up to 234 mm were measured; the settled water turbidity ranged from 5 to 8 NTU and did not appear to reach a consistent value. The run lasted about 39 hours.

In summary, it appears that the media, both the mixed ceramic media and the 1/4-inch polypropylene media, are retaining particles (the effluent turbidity from the flocculator is significantly less than the influent turbidity, and the headloss builds up over time), but the effluent contains few settleable floc particles. Either floc are not being produced in the bed due to inadequate mixing and contact opportunities, or floc are being produced but particle size is limited due to shear forces associated with turbulent mixing conditions within the bed. WE believe the latter to be the case because of our observations that particles are indeed being retained in the bed.

Plans for February:

The mixed ceramic media will be compared with 1/2-inch ceramic media in parallel column runs to determine if floc are being sheared in the bed with the smaller media. The objective is to determine the effect of the larger pore size associated with the 1/2-inch media on the production of settleable floc. The flocculator will then be modified to provide for operation as a tapered bed. If the larger media proves to be advantageous, two media sizes will be used over the larger media in order to provide additional tapered mixing.

TABLE 1.

$$G = \left(\frac{\Delta h \;\; \rho \;\; g \; Q}{\mu \;\; \varepsilon_o \; V} \right)^{1/2}$$

where

Δh = head loss
ρ = density
g = gravitational constant
Q = flow rate
μ = dynamic viscosity
ε_o = porosity
V = total bed volume

Jartest   Date: 01/08/91

Water: Tap water from outside tanks
Temp.: 12.0 C
Coagulant: $FeCl_3$
Turbidity: 200 NTU as Kaolinite
Alkalinity: $NaHCO_3$ 42 mg/l additional

Jar	1	2	3	4	5	6
Parameter						
FeCl3mg/l	2.0	5.0	8.0	10.0	15.0	0.0
Init. pH	7.4	7.4	7.4	7.4	7.4	7.4
Init.Turb	172.0	175.0	174.0	170.0	174.0	174.0
removal						
5 min	147.0	14.7	9.8	3.5	3.7	150.0
20 min	102.0	13.2	6.1	1.2	4.7	121.0
removal/%	40.7	92.5	96.5	99.3	97.3	30.5
pH	7.15	7.00	6.95	6.85	6.65	7.40

Remarks

Rapid mix for two minutes
5 min at 60 RPM
5 min at 30 RPM
5 min at 15 RPM

==> Flocs began forming and settling during rapid mix in jar 5

Jartest Date: 01/08/91

Polymer dosage for high turbidity and low temperature

Water:	Tap water from outside tanks		
Temp.:	12.0 C		
Coagulant:	Al2(SO4)3*14H2O (three month old)		
Turbidity:	200 NTU	as Kaolinite	
Alkalinity: NaHCO3	42 mg/l	additional	

Jar	1	2	3	4	5	6
Parameter						
alum/mg/l	20.0	25.0	20.0	25.0	20.0	25.0
Poly/mg/l	0.0	0.0	0.1	0.1	0.5	0.5
Init. pH	7.7	7.7	7.7	7.7	7.7	7.7
Init.Turb with alum	172.0	175.0	179.0	178.0	179.0	175.0
removal						
5 min	26.0	14.6	8.0	4.6	6.0	10.0
20 min	4.6	6.0	4.0	2.3	3.9	6.0
removal/%	97.3	96.6	97.8	98.7	97.8	96.6
pH	7.00	6.95	7.05	6.95	7.05	7.00

Remarks

Alum and polymer added at the same time .
Rapid mix for two minutes
Tapered flocculation of :
5 min at 60 RPM
5 min at 30 RPM
5 min at 15 RPM

0.5 mg/l of polymer overdosed the system

Jartest Date: 01/08/91

Temperature effects on flocculation

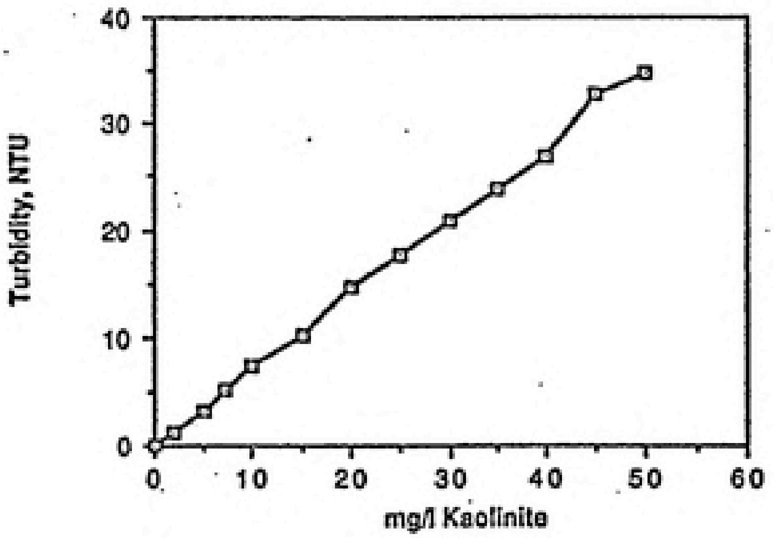
Water: Water from outside tanks and hot tap water.
Temp.:
Coagulant: Al2(SO4)3*14H2O (three month old)
Turbidity: 20 NTU as Kaolinite
Alkalinity: NaHCO3 42 mg/l additional

Jar	1	2	3	4	5	6
Parameter						
alum/mg/l	25.0	25.0	25.0	25.0	25.0	25.0
Poly/mg/l	0.5	0.5	0.5	0.5	0.5	0.5
Init. pH	7.7	7.8	7.8	7.9	7.9	7.9
Init.temp.	6.1	7.4	8.6	9.4	10.6	12.7
Init.Turb with alum	18.6	18.0	18.5	19.0	18.0	17.0
removal						
5 min	10.0	10.0	9.5	8.6	7.0	5.7
20 min	4.3	3.9	3.4	3.2	2.6	2.3
removal/%	76.9	78.3	81.6	83.2	85.6	86.5
pH	6.80	6.80	6.80	6.85	6.80	6.75

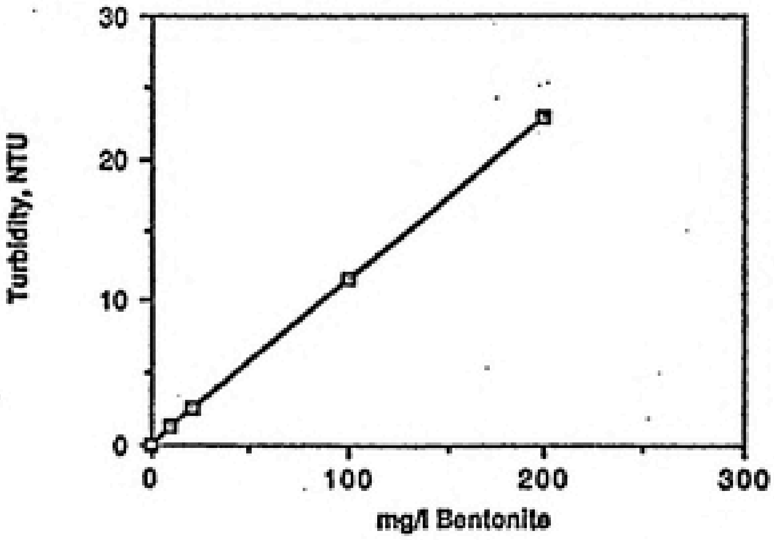
Remarks

Alum and polymer added at the same time .
Rapid mix for two minutes
Tapered flocculation of :
5 min at 60 RPM
5 min at 30 RPM
5 min at 15 RPM

KAOLINITE CALIBRATION CURVE



BENTONITE CALIBRATION CURVE



a:\coag\01-09-91.doc

COAGULATION RUN #5 01/09/91 -/

FEED WATER CHARACTERISTICS:

Turbidity:	20..200	NTU
TOC:		mg/l
Coagulant: Al2(SO4)3*14H2O	25	mg/l
Polymer:	0.1..0.2	mg/l
Alkalinity: NaHCO3	42	mg/l
Raw water pH		
Raw water pH (with alum)	6.6..7.05	
Temperature:	9 ..10	C

Column: I

Media: 1/4 " PP B.-Height 5.7 '

SAMPLE #	FLOWRATE GPM	TIME min	HEADLOSS mm	G -VALUE 1/s	TURBIDITY, NTU EFFLUENT	SETTLED	FEED SETTLED
1	10	0	46	61.0			14.0
2	10	30	51	64.2	115.0	84.0	14.0
4	10	90	54	66.1	147.0	62.0	16.0
5	10	135	57	67.9	112.0	59.0	6.9
6	10	150	70	75.2			22.0
7	10	180	66	73.0	62.0	63.0	10.0
8	10	210	70	75.2	90.0	50.0	2.5
9	10	255	76	78.4	88.0	42.0	5.1
10	10	300	76	78.4	65.0	44.0	8.0
11	10	360	81	80.9	33.0	14.0	6.0
12	10	420	91	85.8	13.3	9.0	4.2
13	10	480	102	90.8	15.0	10.7	2.0
14	10	540	109	93.9	12.0	10.4	2.5

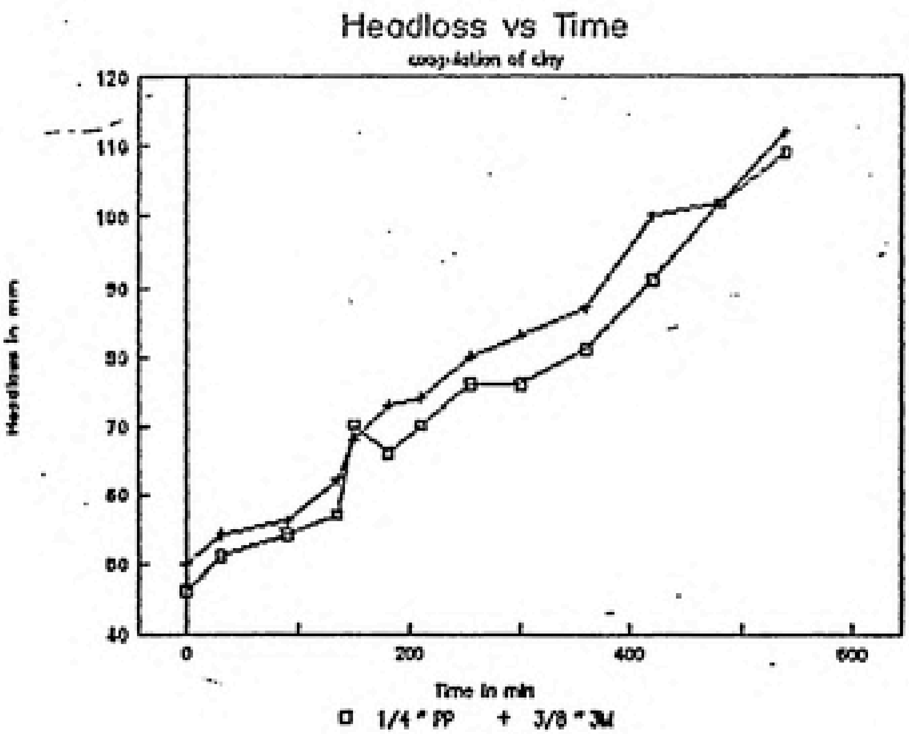
Column: II

Media: 3/8 " 3M B.-Height 5.0 '

SAMPLE #	FLOWRATE GPM	TIME min	HEADLOSS mm	G -VALUE 1/s	TURBIDITY, NTU EFFLUENT	SETTLED	FEED SETTLED
1	10	0	50	63.6			14.0
2	10	30	54	66.1	112.0	87.0	14.0
4	10	90	56	67.3	130.0	73.0	16.0
5	10	135	62	70.8	122.0	70.0	6.9
6	10	150	68	74.1			22.0
7	10	180	73	76.8	72.0	65.0	10.0
8	10	210	74	77.4	101.0	58.0	2.5
9	10	255	80	80.4	85.0	52.0	5.1
10	10	300	83	81.9	63.0	49.0	8.0
11	10	360	87	83.9	25.0	23.0	6.0
12	10	420	100	89.9	12.1	9.3	4.2
13	10	480	102	90.8	15.0	10.4	2.0
14	10	540	112	95.2	18.0	18.0	2.5

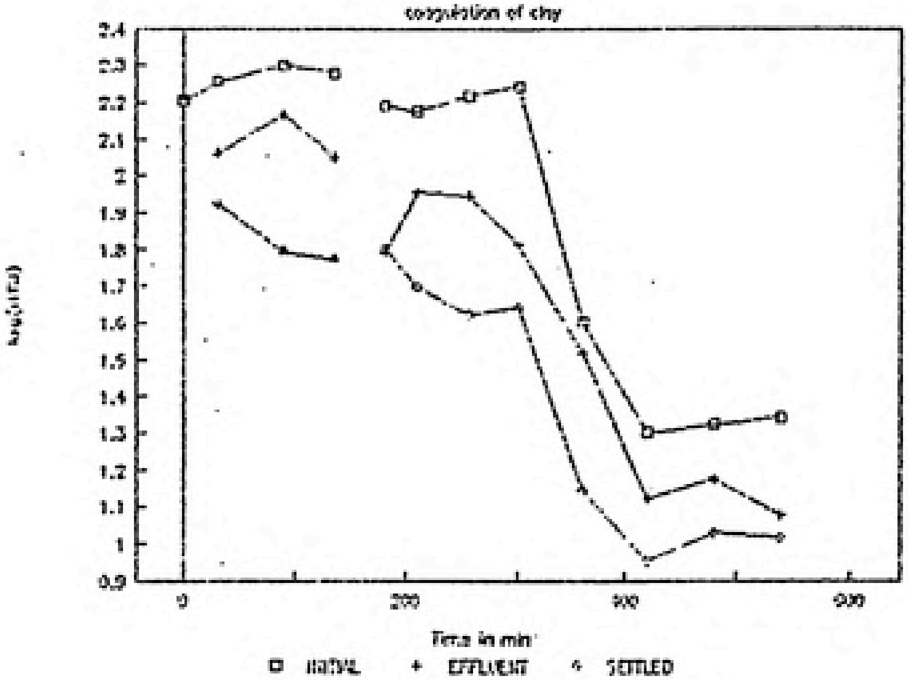
Remarks

At 12:30 (#3) polymerdose was doubled due to unexpected low tempeature.
At 1:15 pm bad performance led to jartest and new chemical adjustment: Polymer: 0.5 mg
Alum: 30.0 mg/l
At 6:00 (#10) turbidity was lowered. Rate of headloss kept being constant!!



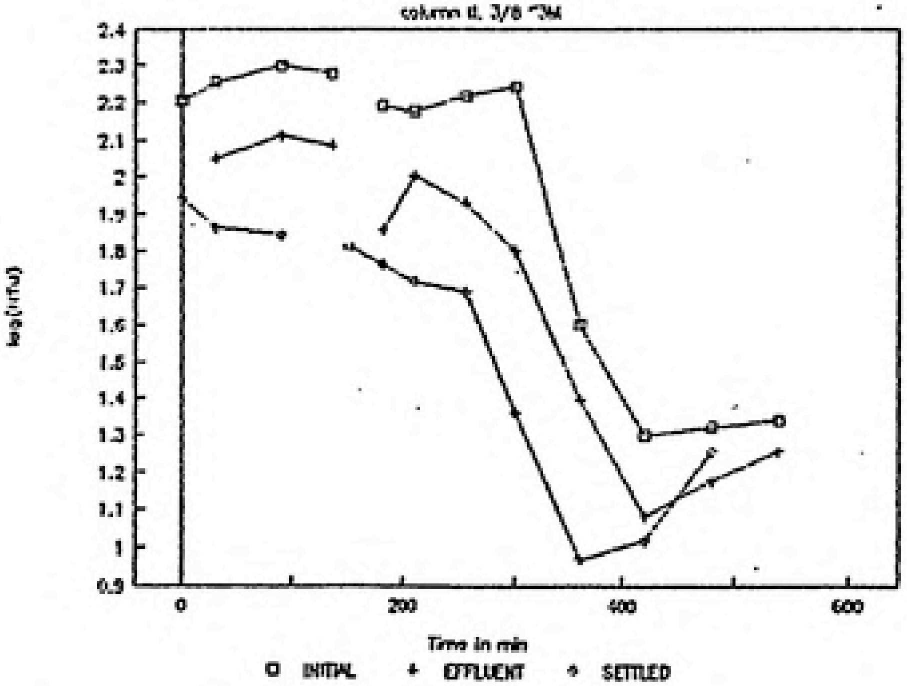
Turbidity vs Time

coagulation of clay



Turbidity vs Time

column II, 3/8



COAGULATION RUN 01/15/91

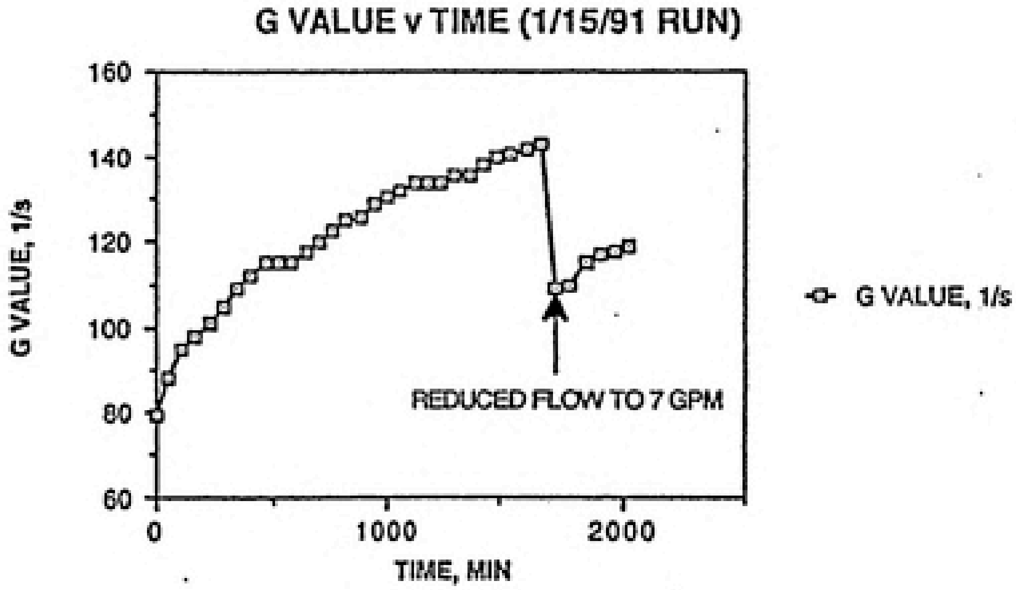
FEED WATER CHARACTERISTICS:

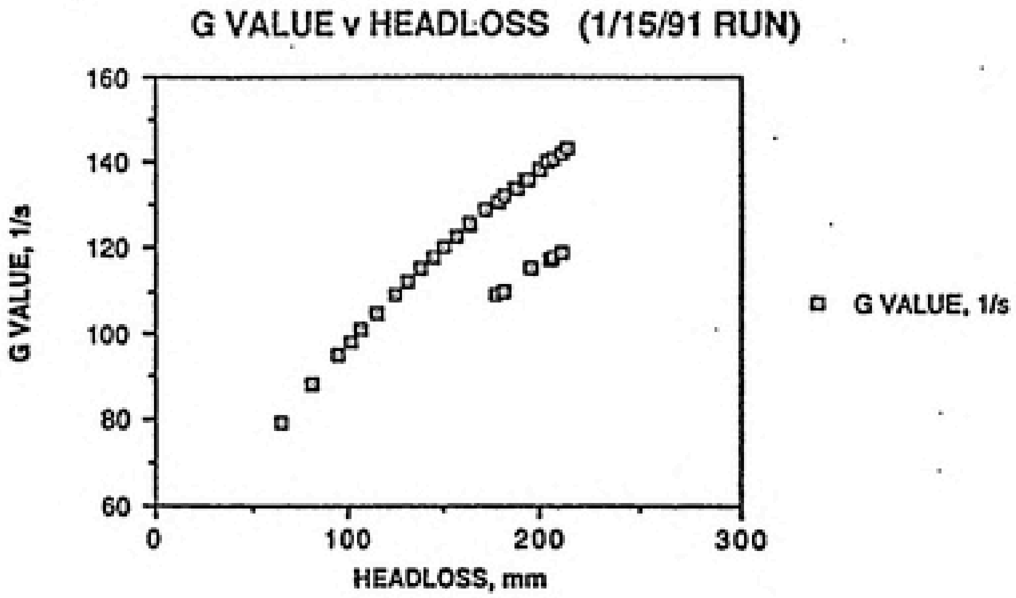
Turbidity:	19..27	NTU
Coagulant: Al2(SO4)3*14H2O	25	mg/l
Polymer:	0.3	mg/l
Alkalinity: NaHCO3	63	mg/l
Raw wate pH (with alum)	6.7..7.1	
Temperature:	10..11	C
Media: 3/8 " 3M	Bed Heigh 5.0 FT	

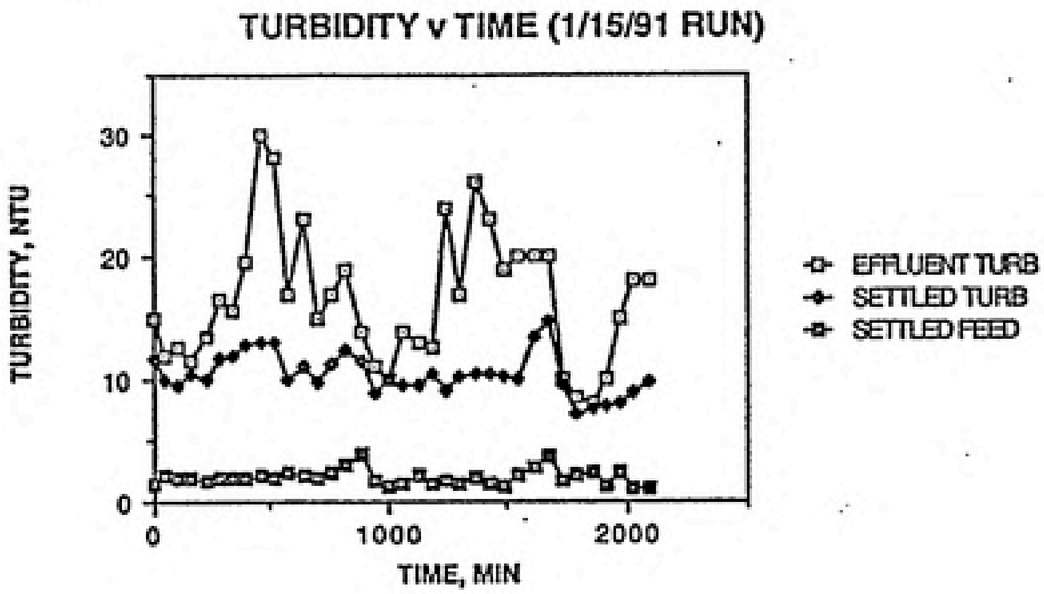
SAMPLE #	FLOWRATE GPM	TIME min	HEADLOSS mm	TURBIDITY, NTU EFFLUENT	SETTLEC	SETTLED FEED	G VALUE 1/s
1	10	0	65	15.0	11.7	1.5	79
2	10	45	82	12.0	10.0	2.2	88
3	10	105	94	12.5	9.5	1.9	95
4	10	165	101	11.5	10.4	2.0	98
5	10	225	107	13.5	10.1	1.8	101
6	10	285	115	16.5	11.7	1.9	105
7	10	345	125	15.7	11.9	1.9	109
8	10	405	131	19.5	12.8	1.9	112
9	10	465	138	30.0	13.1	2.1	115
10	10	525	138	28.0	13.0	1.9	115
11	10	585	139	17.0	10.1	2.4	115
12	10	645	145	23.0	11.0	2.1	118
13	10	705	151	15.0	9.7	2.0	120
14	10	765	158	17.0	11.3	2.4	123
15	10	825	164	19.0	12.3	3.1	125
16	10	885	165	14.0	11.5	4.0	126
17	10	945	173	11.0	9.0	1.8	129
18	10	1005	179	10.0	10.0	1.4	131
19	10	1065	182	14.0	9.5	1.5	132
20	10	1125	187	13.0	9.5	2.2	134
21	10	1185	187	12.5	10.5	1.5	134
22	10	1245	189	24.0	9.2	1.7	134
23	10	1305	193	17.0	10.2	1.6	136
24	10	1365	194	26.0	10.4	2.0	136
25	10	1425	200	23.0	10.5	1.6	138
26	10	1485	204	19.0	10.3	1.3	140
27	10	1545	207	20.0	10.1	2.1	141
28	10	1605	211	20.0	13.5	2.8	142
29	10	1665	214	20.0	14.8	3.6	143
30	7	1725	178	10.0	9.5	1.7	109
31	7	1785	182	8.5	7.2	2.1	110
32	7	1845	196	8.0	7.7	2.4	115
33	7	1905	205	10.0	7.8	1.3	117
34	7	1965	207	15.0	8.1	2.4	118
35	7	2025	211	18.0	9.0	1.1	119
36	7	2085	211	18.0	9.7	1.1	119

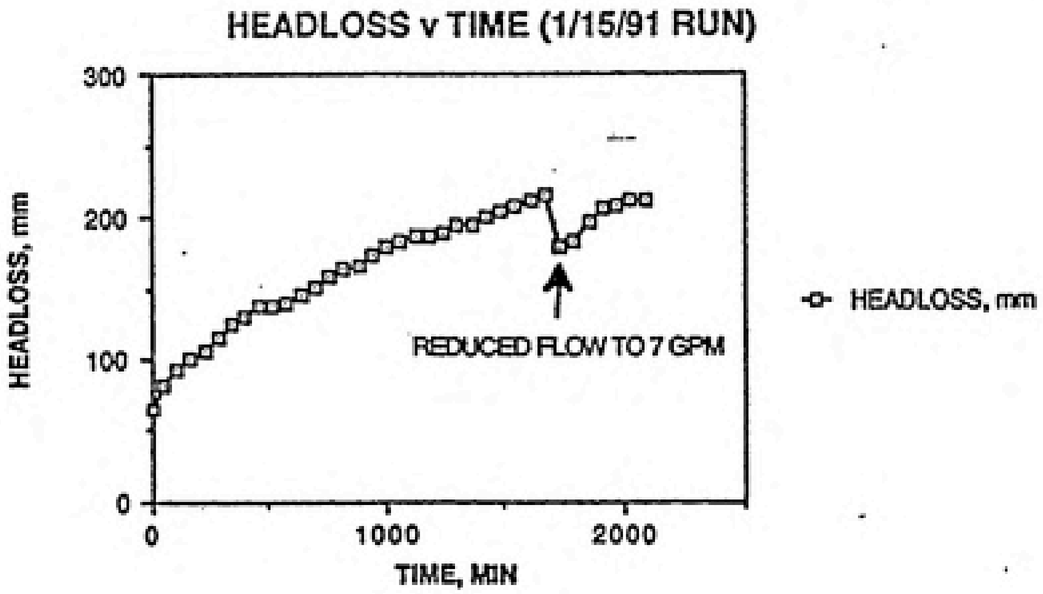
Procedures / Remarks

* Taking initial samples directly from the outlet causes shocks to the system. Large volumes of floc can be observed coming out of the bed.
* Due to settling in the jar while taking effluent sample, turbidity was measured directly from the line beginning with sample#8.
* Startup and change in flowrate caused loss of head.


G VALUE v TIME (1/15/91 RUN)
G VALUE, 1/s
160
140
120
100
80
60
0
1000
2000
TIME, MIN
REDUCED FLOW TO 7 GPM
G VALUE, 1/s


G VALUE v HEADLOSS (1/15/91 RUN)
G VALUE, 1/s
160
140
120
100
80
60
0
100
200
300
HEADLOSS, mm
G VALUE, 1/s


TURBIDITY v TIME (1/15/91 RUN)
TURBIDITY, NTU
30
20
10
0
1000
2000
TIME, MIN
EFFLUENT TURB
SETTLED TURB
SETTLED FEED


HEADLOSS v TIME (1/15/91 RUN)
HEADLOSS, mm
300
200
100
0
1000
2000
TIME, MIN
REDUCED FLOW TO 7 GPM
HEADLOSS, mm

a:\coag\1-23-91.wk1

COAGULATION RUN #7 01/23/91

FEED WATER CHARACTERISTICS:

Turbidity:	16..23	NTU
TOC:		mg/l
Coagulant: Al2(SO4)3*14H2O	25	mg/l
Polymer:	0.3	mg/l; see remarks
Alkalinity: NaHCO3	63	mg/l
Raw water pH		
Raw water pH (with alum)	6.7..7.1	
Temperature:	10.3..10.6 C	

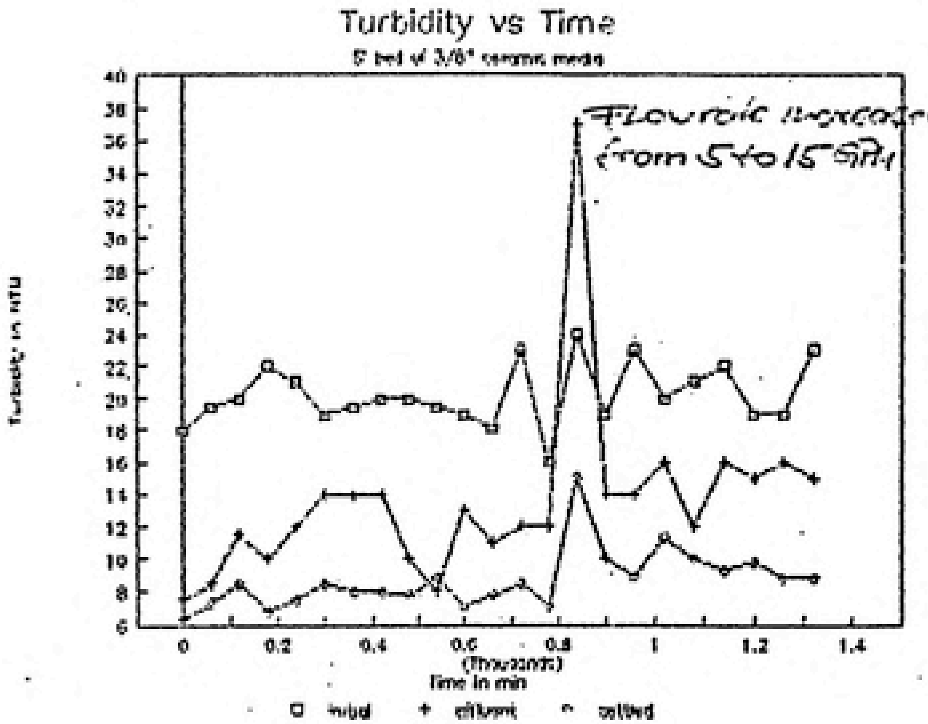
Column: II

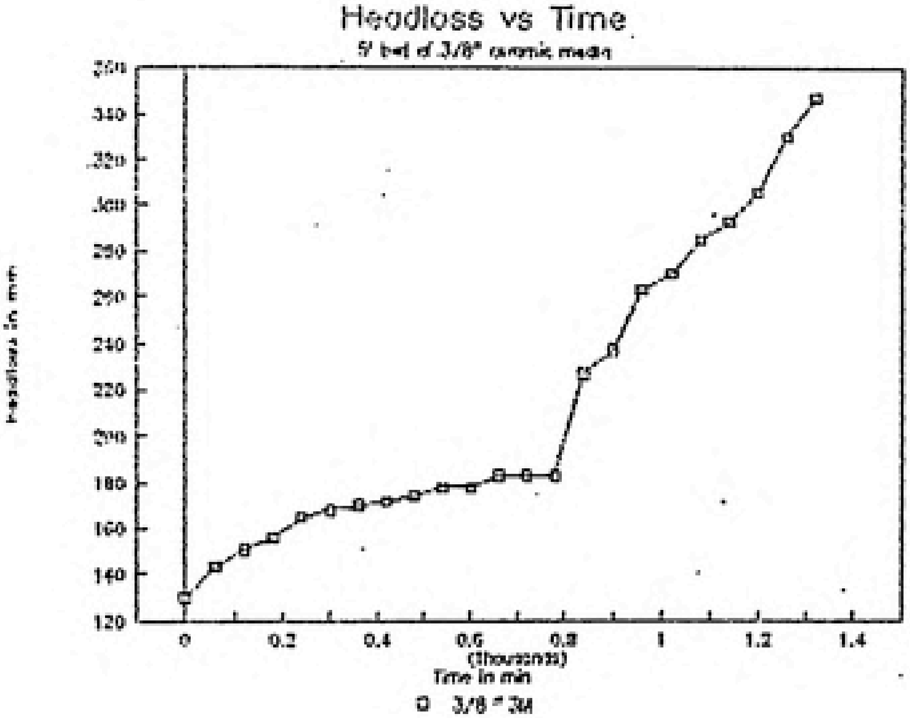
Media: 3/8 " 3M B.-Height 5.0 '

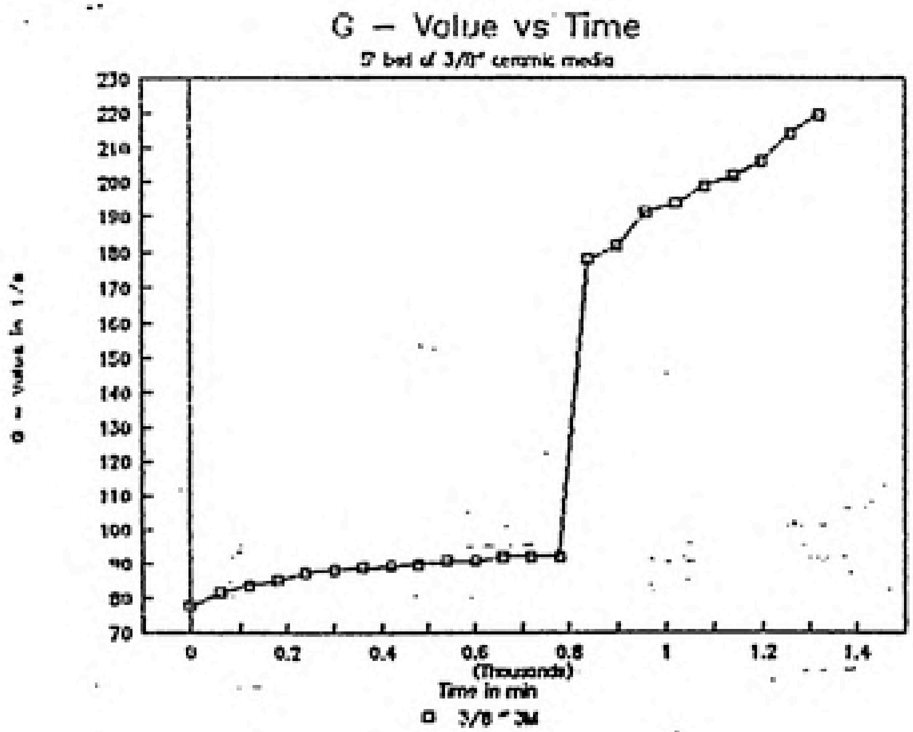
SAMPLE #	FLOWRATE GPM	TIME min	HEADLOSS mm	G - VALUE 1/s	TURBIDITY,NTU EFFLUENT	SETTLED	FEED SETTLED
1	5	0	130	77.6	7.5	6.4	1.7
2	5	60	143	81.4	8.5	7.3	2
4	5	120	151	83.7	11.5	8.5	2.9
5	5	180	156	85.0	10.0	6.9	2.6
6	5	240	165	87.4	12.0	7.5	1.2
7	5	300	168	88.2	14.0	8.5	1.7
8	5	360	170	88.8	14.0	8.0	1.7
9	5	420	172	89.3	14.0	8.0	1.9
10	5	480	174	89.8	10.0	7.8	1.7
11	5	540	178	90.8	8.0	8.8	1.4
12	5	600	178	90.8	13.0	7.1	1.2
13	5	660	183	92.1	11.0	7.8	2.1
14	5	720	183	92.1	12.0	8.5	1.8
15	5	780	183	92.1	12.0	7.1	1.7
16	15	840	227	177.6	37.0	15.0	1.4
17	15	900	237	181.5	14.0	10.0	1.8
18	15	960	263	191.2	14.0	8.9	2.2
19	15	1020	270	193.7	16.0	11.3	2.5
20	15	1080	285	199.1	12.0	10.0	1.8
21	15	1140	293	201.8	16.0	9.3	1.9
22	15	1200	306	206.3	15.0	9.8	1.8
23	15	1260	330	214.2	16.0	8.8	3.4
24	15	1320	347	219.6	15.0	8.8	1.7

Procedures / Remarks

* Taking initial samples direct from the outlet causes shocks to the whole system.
* Due to settling while taking effluent sample, turbidity was measured directly from the line from #8 on.
* Start and the change of flowrate caused heavy loss in head.
* Constant pressure and therefore flow is required to achieve comparable results.
* At time=1000 minutes, the level in the tanks was lowered one foot to accomodate large head buildup.
* Readings of effluent samples were difficult due to large amount of heavy flocs and therefore sedimentation.
* Polymerdose was increased to 0.4 mg/l at t= 180 min


Turbidity vs Time
5' bed of 3/8" ceramic media
Flouroic increased
from 5 to 15 gpm
Turbidity in NTU
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
0
0.2
0.4
0.6
0.8
1
1.2
1.4
(Thousands)
Time in min
initial
effluent
settled


Headloss vs Time
5' bed of 3/8" ceramic media
Headloss in mm
Time in min
(Thousands)
3/8 " 3M


G – Value vs Time
5' bed of 3/8" ceramic media
G – Values in 1/s
Time in min
(Thousands)
3/8 " 3M

COAGULATION RUN 01/31/91

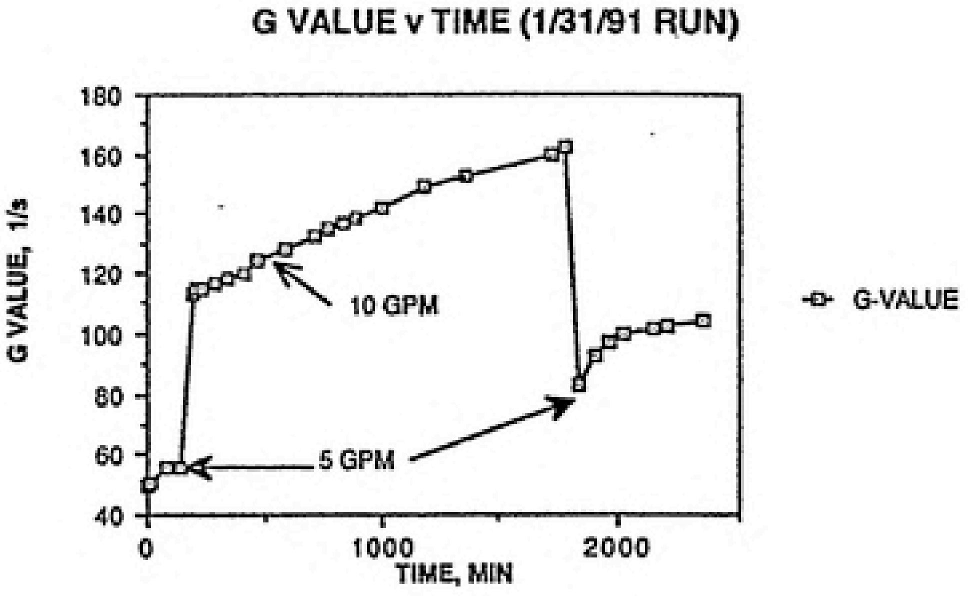
FEED WATER CHARACTERISTICS:

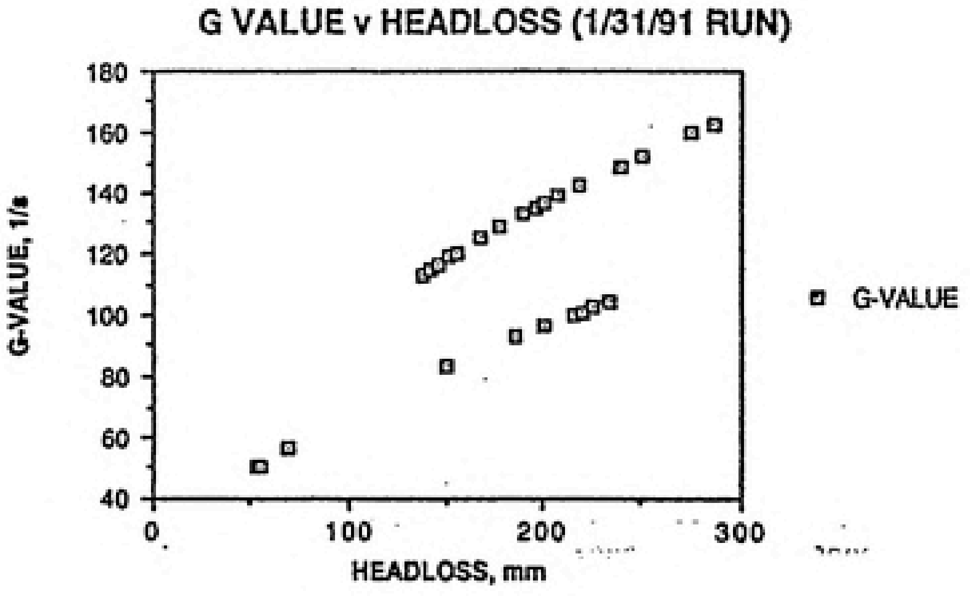
Turbidity:	20	NTU
TOC:		mg/l
Coagulant : FeCl	11	mg/l
Polymer:	0	mg/l; see remarks
Alkalinity: NaHCO3	73	mg/l
Raw water pH		
Raw water pH with FeCl	6.7..7.1	
Temperature:	10.4..10.6 C	

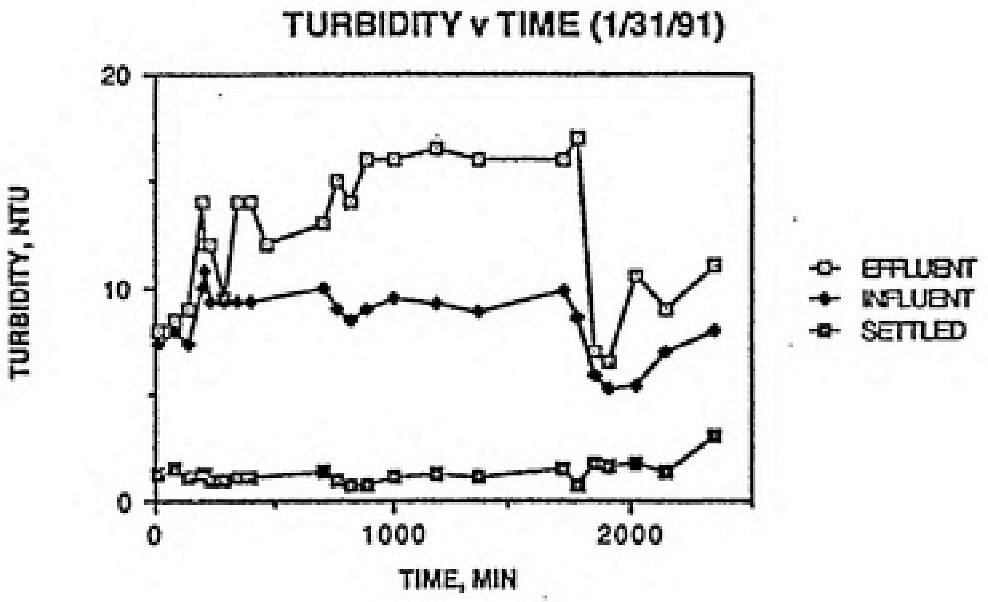
Column: II

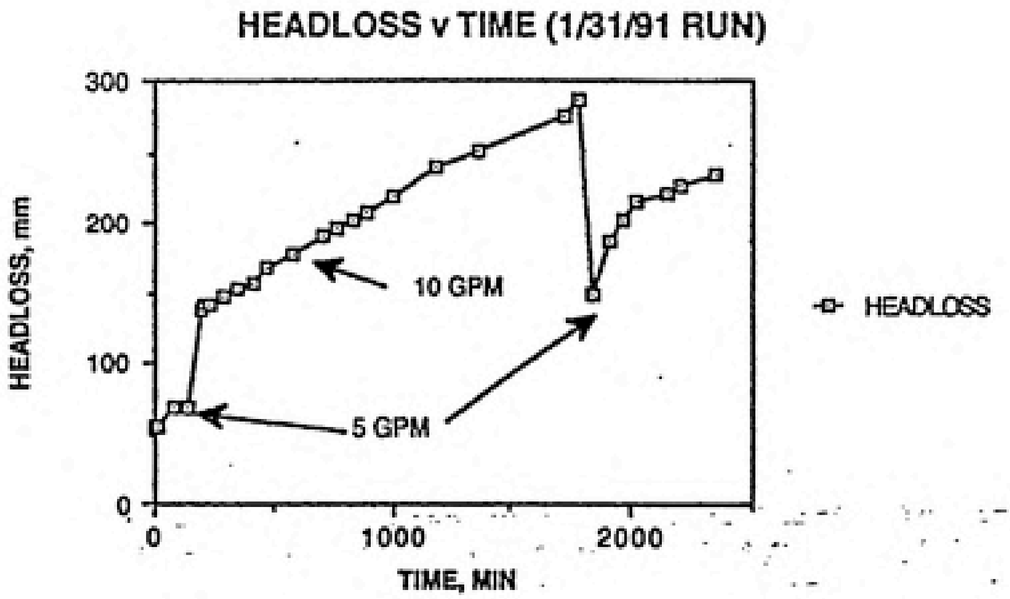
Media: 3/8 " 3M B.-Height 5.0 '

SAMPLE #	FLOWRATE GPM	TIME min	HEADLOSS mm	G - VALUE 1/s	TURBIDITY,NTU EFFLUENT	SETTLED	FEED SETTLED
0	5	0	54	50.0			
1	5	15	55	50.5	8.0	7.3	1.2
2	5	75	68	56.1	8.5	7.9	1.5
3	5	135	68	56.1	9.0	7.3	1.1
4	10	195	138	113.1	14.0	10.0	1.3
5	10	210	142	114.7	12.0	10.8	1.3
6	10	225	142	114.7	12.0	9.3	1
7	10	285	147	116.7	9.5	9.3	1
8	10	345	152	118.7	14.0	9.3	1.1
9	10	405	156	120.2	14.0	9.3	1.1
10	10	465	168	124.8	12.0		
11	10	585	178	128.4			
12	10	710	190	132.7	13.0	10.0	1.4
13	10	765	197	135.1	15.0	9.0	1
14	10	825	201	136.5	14.0	8.5	0.7
15	10	885	208	138.8	16.0	9.0	0.8
16	10	1005	219	142.5	16.0	9.5	1.1
17	10	1185	240	149.1	16.5	9.2	1.2
18	10	1365	251	152.5	16.0	8.8	1.1
19	10	1725	276	159.9	16.0	9.8	1.5
20	10	1785	286	162.8	17.0	8.6	0.7
21	5	1845	150	83.4	7.0	5.8	1.8
22	5	1905	186	92.8	6.5	5.2	1.6
23	5	1965	202	96.8			
24	5	2025.	216	100.0	10.5	5.3	1.7
25	5	2145	221	101.2	9	7	1.4
26	5	2205	226	102.3			
27	5	2355	234	104.1	11	8	3


G VALUE v TIME (1/31/91 RUN)
G VALUE, 1/s
TIME, MIN
10 GPM
5 GPM
G-VALUE


G VALUE v HEADLOSS (1/31/91 RUN)
G-VALUE, 1/s
HEADLOSS, mm
G-VALUE


TURBIDITY v TIME (1/31/91)
TURBIDITY, NTU
20
10
0
0
1000
2000
TIME, MIN
EFFLUENT
INFLUENT
SETTLED


HEADLOSS v TIME (1/31/91 RUN)
HEADLOSS, mm
300
200
100
0
0
1000
2000
TIME, MIN
10 GPM
5 GPM
HEADLOSS

Monthly Progress Report / Buoyant Coarse Media Flocculator

February, 1991

This month we made two pilot scale flocculation runs at turbidities of 20 NTU of kaolinite and at flow rates of 5 and 8 GPM. Ferric chloride was used as the coagulant in both runs; no polymer was used. Both of these runs used ceramic 3M media, followed by Norpak. The Norpak was in an upflow orientation in the overflow column in one run and directly followed the ceramic media in a downflow orientation in the other run. At the end of the month the tapered media bed was designed, fabricated, and installed. The results are presented below as bullets, with supporting data attached.

- On February 7, a coagulation run was made with a five foot bed of 3/8" mixed ceramic media in the flocculator followed by a 4-1/2 foot bed of 3/4" Norpak media in the overflow column. Operating conditions were 5 GPM flowrate, 20 NTU of influent turbidity, and 11 mg/l ferric chloride. The run lasted for 27 consecutive hours. Headloss ranged from 221 to 227 mm, corresponding to G values of 101 to 117 1/s. Effluent turbidities out of the flocculator averaged 14 NTU with settled turbidities averaging 7 NTU. Turbidities out of the overflow column averaged 6 NTU with settled turbidities averaging 5 NTU. Twenty minute settled turbidities of near 3 NTU were obtained in several samples from the overflow column. It should be noted that the large variance in turbidity in the overflow column was the result of difficulty in sampling without shearing flocs or disturbing the bed. In addition, some of the flocs coming from the Norpak bed were far larger than any of the floc observed from the ceramic bed.

- On February 11, a coagulation run was made using both columns configured with ceramic media on top followed by Norpak. In column 1, 2-1/2 feet of 1/2" ceramic media and 2-1/2 feet of 3/4" Norpak were used. In column 2, 2-1/2 feet of 3/8" mixed ceramic media was used with 2-1/2 feet of 3/4" Norpak. Operating conditions were initially 8 GPM per column (flow reduced to 5 GPM after 9 hours), 20 NTU of influent turbidity, and 14 mg/l of ferric chloride. Headloss in column 1 ranged from 12 to 98 mm and from 18 to 127 in column 2. G values for column 1 ranged from 26 to 58 1/s and from 32 to 66 1/s for column 2. Column 1 was run for 61 hours while column 2 was shutdown after 16.5 hours to conserve water. Results from column 1 were effluent turbidities averaging 10 NTU and settled turbidities averaging 9 NTU. Effluent turbidity from column 2 averaged 7.5 NTU and settled turbidity averaged 7 NTU. Due to the shearing of very large flocs leaving both columns, settled turbidities were highly dependent upon sampling rate. This problem became apparent late in the run when more large floc were being released from the Norpak.

- During the last two weeks of February a tapered bed was fabricated which will allow for tapering at either 30 or 45 degrees. The cross-sectional area of the bed will range from 1 to 4 square feet. Currently the 30 degree orientation has been installed. By tapering the bed and layering the media, we intend to take advantage of the decreasing G value as flow progresses through the bed. This will provide an opportunity to form and release larger flocs. An improved sampling technique which allows for sampling through 1-1/4" tubing will also be employed in an effort to eliminate the floc shearing which occurred in the 3/8" tubing previously used.

In summary, it appears that the Norpak media allows for the formation and release of larger flocs. It also appears that our sampling technique through 3/8" tubing cannot collect these larger flocs without shearing them.

Plans for March:

The tapered bed will first be filled with a layered media of 3/8" ceramic on top of 1/2" ceramic on top of 3/4" ceramic. Headloss and tracer test studies will then be run. The bed will then be run with the layered, tapered bed. Next the same configuration will be used in the flocculator followed by Norpak in an upflow orientation in the overflow column.

COAGULATION RUN # 9 02/07/91

FEED WATER CHARACTERISTICS:

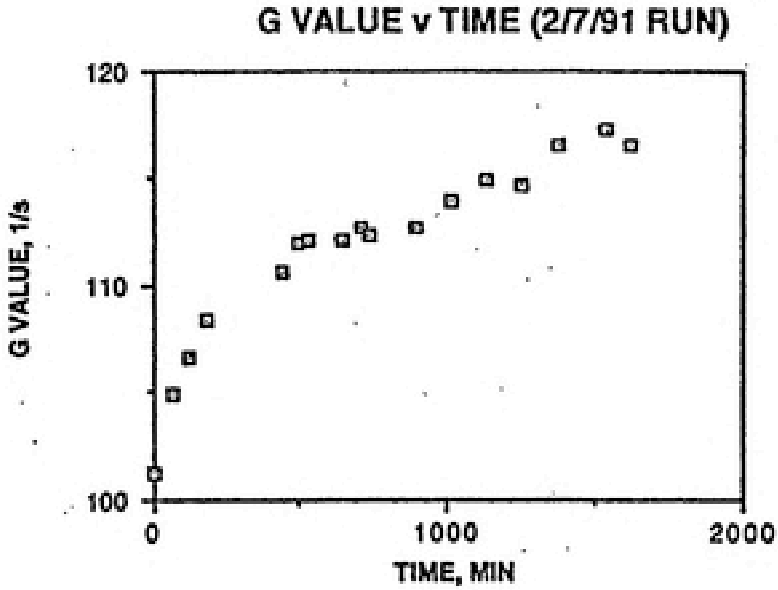
Turbidity:	20	NTU
Coagulan: FeCl	11	mg/l
Polymer:	0	mg/l
Alkalinity: NaHCO3	84	mg/l
Raw wate pH with FeCl	6.7..7.1	
Temperature:	10.4..10.6 C	

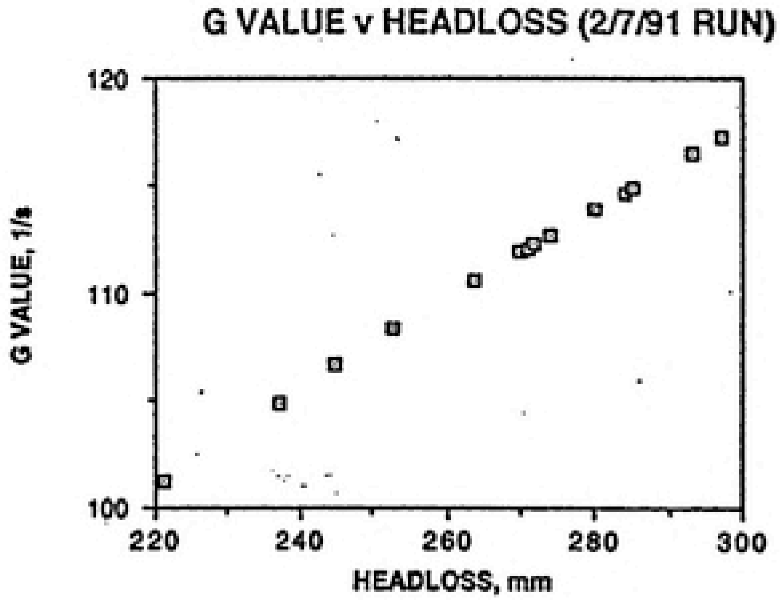
Media:	3/8 " 3M	B.-Height	5.0 '	Downflow
	3/4 " NP	B.-Height	4.2 '	Upflow

SAMPLE	TIME	HEADLOSS	G - VALUE	Column TURBIDITY,NTU		Overflow TURBIDITY,NTU		
#	h	mm	1/s	EFFLUENT	SETTLED	EFFLUENT	SETTLED	FEED SETTLED
0	0.0	221	101.2	23.0				
1	1.0	237	104.8	8.0	6.5	11.0	10.0	3.3
2	2.0	245	106.6	11.0	5.6	4.7	3.3	1.7
3	3.0	253	108.3	12.0		5.0	3.4	0.9
4	7.5	264	110.6	14.0	8.3	9.0	7.7	1.5
5	8.3	270	111.9	23.0		5.4		2.3
6	9.0	271	112.1	15.0	7.5	5.6	5.2	3.8
7	11.0	271	112.1	14.0	8.3	5.3	4.7	3.0
8	12.0	274	112.7	15.0	8.3	5.2	4.7	2.3
9	12.5	272	112.3	15.0	6.0	4.7	4.2	1.7
10	15.0	274	112.7	14.0	6.5	4.2	3.7	1.6
11	17.0	280	113.9	13.0	7.5	5.0	4.4	1.7
12	19.0	285	114.9	14.0	7.7	6.8	6.6	0.9
13	21.0	284	114.7	16.5	8.4	9.3	8.5	0.9
14	23.0	293	116.5	13.0	7.0	6.9	5.4	1.1
15	25.5	297	117.3	13.0	5.8	7.5	6.8	1.2
16	27.0	293	116.5	12.0	6.2	10.0	9.0	1.2

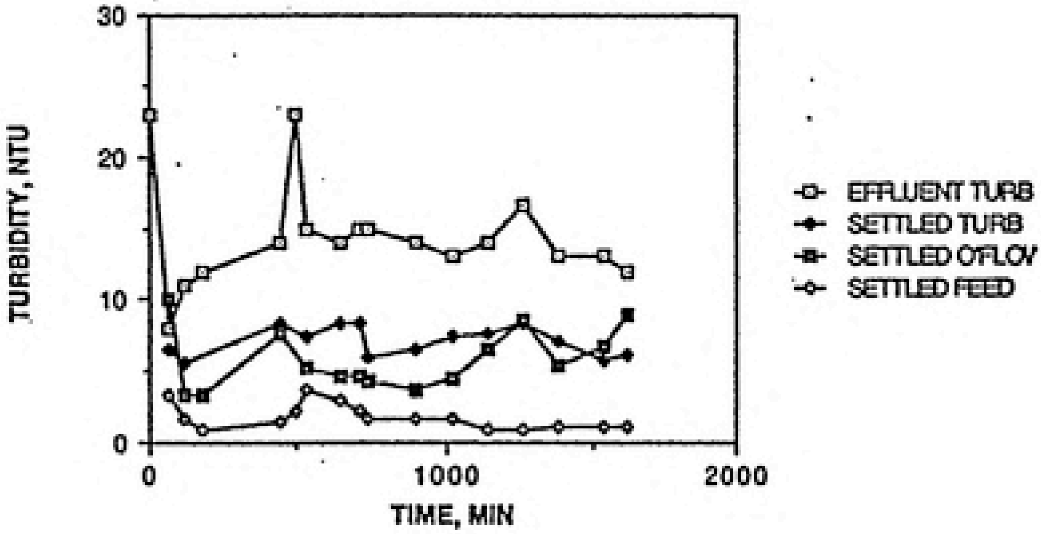
Procedures / Remarks

* Norpak was slightly covered after 15 min and accumulating floc-mass steadily. Only tiny particles left the NP-bed (visual).
* After app. 15h of run time NP Bed was loaded an released big flocs. These flocs were at the size of app. 5 to 6 mm and obviously torn apart from the bed (small particles still remained in the effluent).
* Sampling of overflow samples is questionable because of heavy floc-shearing.
* Steady state porosity of NP in the overflow column was determined (by measuring volume) to be between 0.5 and 0.65.
* Residence time in the NP bed was app. 123 s

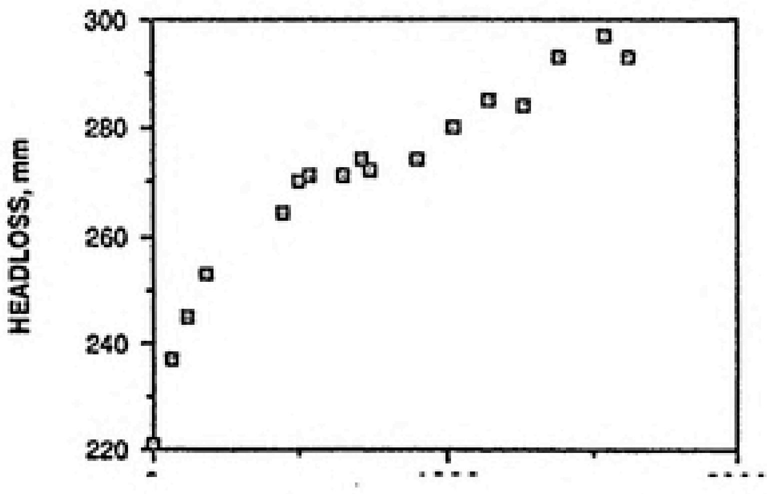

G VALUE v TIME (2/7/91 RUN)
G VALUE, 1/s
120
110
100
0
1000
2000
TIME, MIN


G VALUE v HEADLOSS (2/7/91 RUN)
G VALUE, 1/s
120
110
100
220
240
260
280
300
HEADLOSS, mm

TURBIDITY v TIME (2/7/91 RUN)



HEADLOSS v TIME (2/7/91 RUN)



COAGULATION RUN #10 02/11/91

FEED WATER CHARACTERISTICS:

Turbidity:	20 NTU
Coagulan: FeCl	14 mg/l
Polymer:	0 mg/l; see remarks
Alkalinity: NaHCO3	84 mg/l
Raw wate pH	
Raw wate pH with FeCl	6.7..7.1
Temperature:	11.3..11.6 C

Column: I

Media:				
	1/2 " 3M	B.-Height	2.5 '	Downflow
	3/4 " NP	B.-Height	2.5 '	Downflow

SAMPLE #	TIME h	OVERALL HEADLOSS mm	G - VALUE 1/s	3M TURBIDITY,NTU EFFLUENT	3M TURBIDITY,NTU SETTLED	3M + NP TURBIDITY,NTU EFFLUENT	3M + NP TURBIDITY,NTU SETTLED	FEED SETTLED
0	0.0	12	25.8					1.0
1	1.2	14	27.9	14.3		12.1		0.6
2	3.0	16	29.8	14.0		12.0		0.7
3	5.0	16	29.8	18.0		11.0	11.0	0.5
4	8.0	25	37.3	13.0		11.0	11.0	0.5
5	10.0	21	27.0	11.0		9.7		0.8
6	13.0	25	29.5	12.0		8.9	8.9	0.5
7	16.0	28	31.2	10.9		9.0	8.7	0.7
8	19.0	30	32.3	15.0		11.6	11.0	1.6
9	21.0	34	34.4	14.0	13.0	10.0	10.0	0.8
10	26.0	37	35.9	15.0	13.0	10.0	9.5	0.9
11	31.0	45	39.5	17.0	12.5	10.5	9.7	1.1
12	36.0	57	44.5	22.0	11.7	13.0	10.1	0.8
13	39.0	64	47.2	20.0	15.2	9.6	10.0	0.5
14	44.0	75	51.1	20.0	16.1	11.5	12.0	1.3
15	48.4	83	53.7	14.5	12.5	12.0	9.5	0.7
16	53.3	90	55.9	12.0	11.5	10.0	7.4	0.5
17	61.0	98	58.4	20.0	12.5	11	8.2	0.6

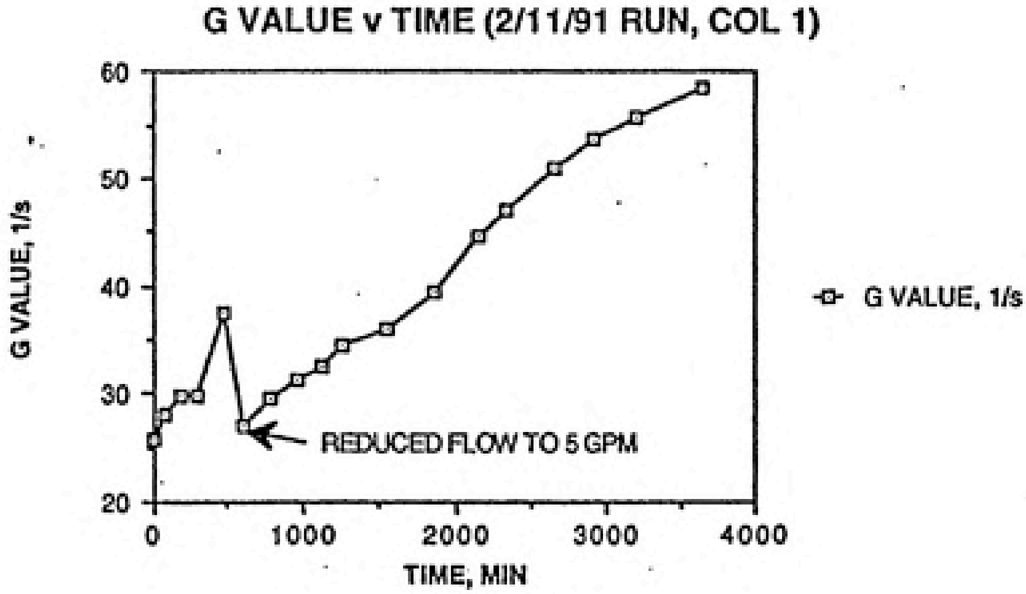
Column: II

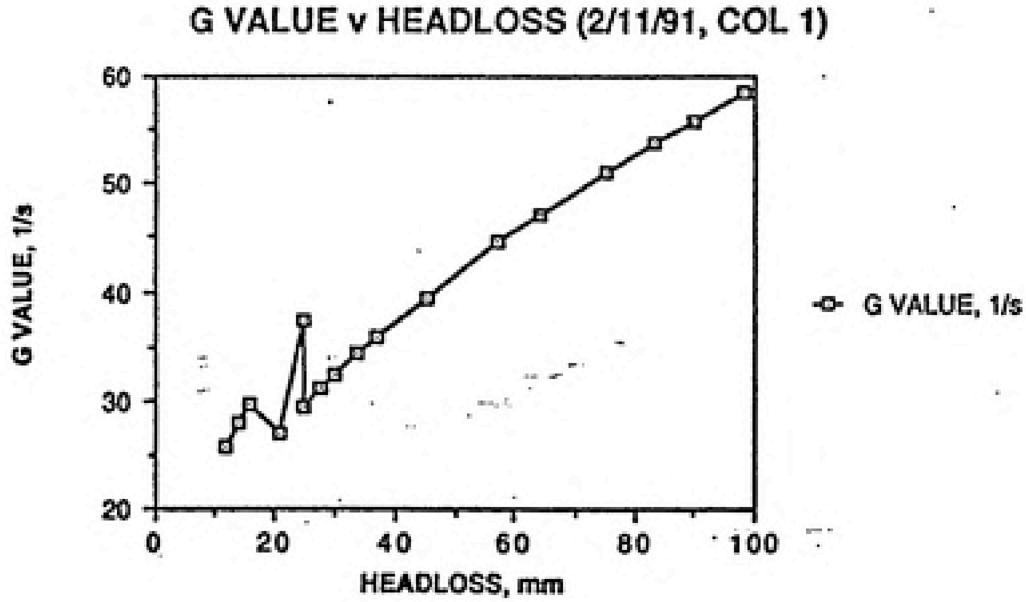
Media: 3/8 " 3M B.-Height 2.5 ' Downflow
3/4 " NP B.-Height 2.5 ' Downflow

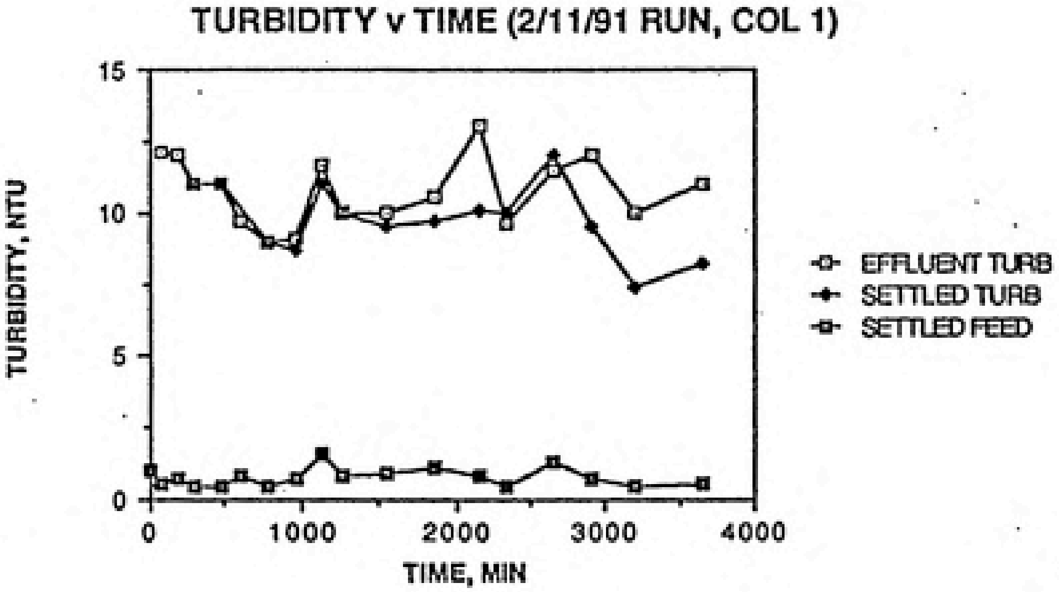
SAMPLE #	TIME h	OVERALL HEADLOSS mm	G - VALUE 1/s	3M TURBIDITY,NTU EFFLUENT	3M TURBIDITY,NTU SETTLED	3M + NP TURBIDITY,NTU EFFLUENT	3M + NP TURBIDITY,NTU SETTLED	FEED SETTLED
0	0.0	18	31.6	12.1				1.0
1	1.2	34	43.5			9.5		0.6
2	3.0	42	48.3	10.0		8.7		0.7
3	5.0	47	51.1	9.0		8.0	7.4	0.5
4	8.0	71	62.8	10.0	7.5	7.1	7.1	0.5
5	10.0	59	45.3	7.9		6.9	7.0	0.8
6	13.0	82	53.4	15.0		6.5	6.3	0.5
7	16.0	93	56.9	25.0	8.3	6.4	6.2	0.7
8	16.0	74	50.7					0.6
9	19.0	107	61.0	15.0	10.1	8.0	7.2	0.5
10	24.5	127	66.4	17.0	11.0	6.6	6.5	1.1

Procedures / Remarks

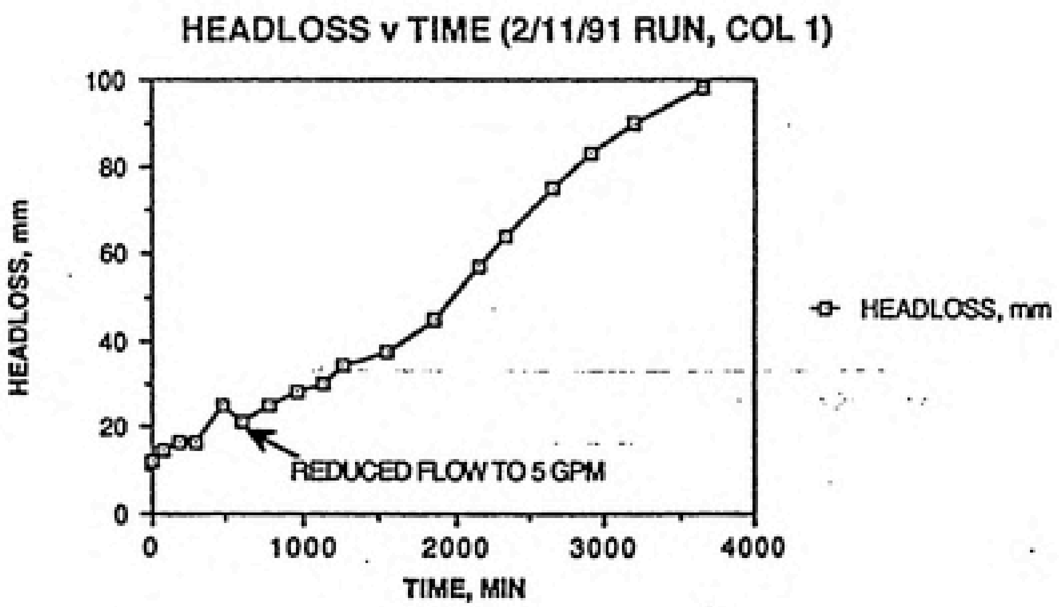
* Both columns were run for the first nine hours at 8 GPM
  The flowrate was reduced to 5 GPM until the end of the run.
* Column I and Column II were run in parallel.
* After 16.5 hours Column II was shut down in order to provide enough water for Column I. At this point the Norpak media in Column II had retained more floc than the Norpak in Column I.
* Some flocs in the size range of app. 5 to 6 mm had sheared from the bed; small particles still remained in the effluent.
* The number of large flocs in the effluent increased throughout the run. However, it was not possible to determine the actual settled water turbidity from the effluent due to significant floc shearing during sampling.


G VALUE v TIME (2/11/91 RUN, COL 1)
G VALUE, 1/s
TIME, MIN
REDUCED FLOW TO 5 GPM
G VALUE, 1/s
20
30
40
50
60
0
1000
2000
3000
4000

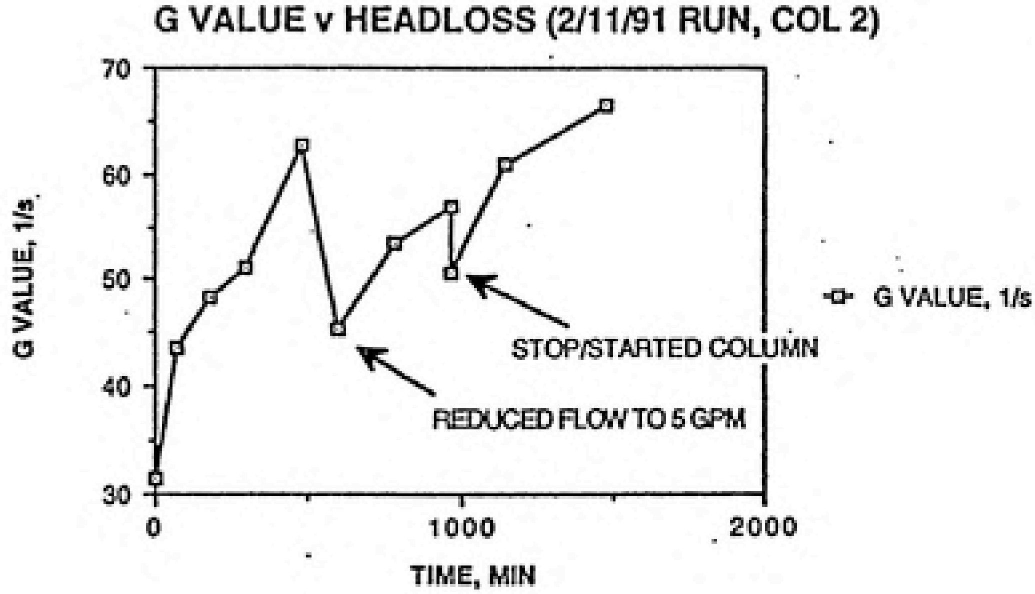

G VALUE v HEADLOSS (2/11/91, COL 1)
G VALUE, 1/s
HEADLOSS, mm
G VALUE, 1/s
20
30
40
50
60
0
20
40
60
80
100

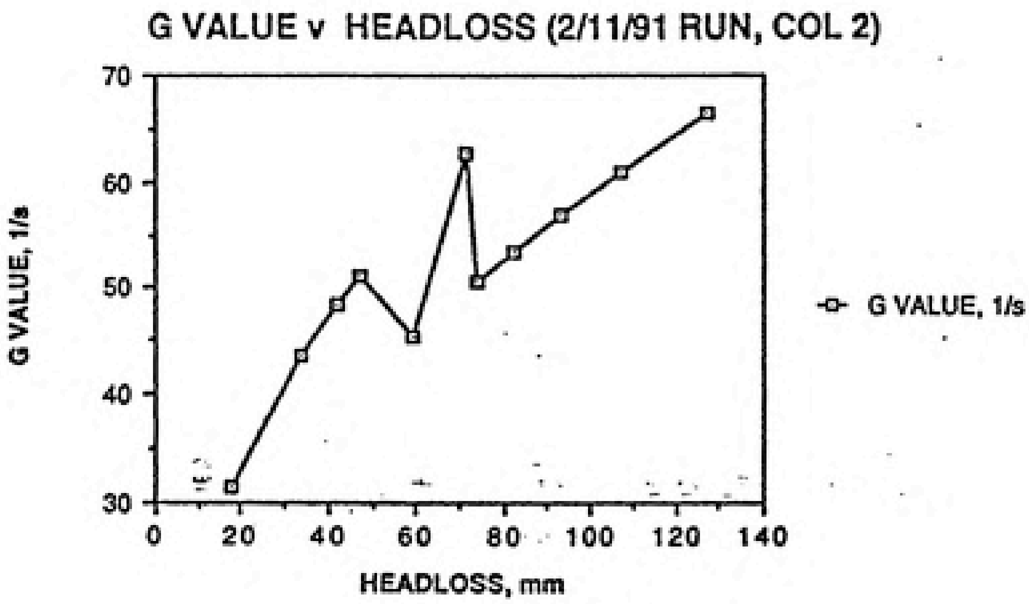


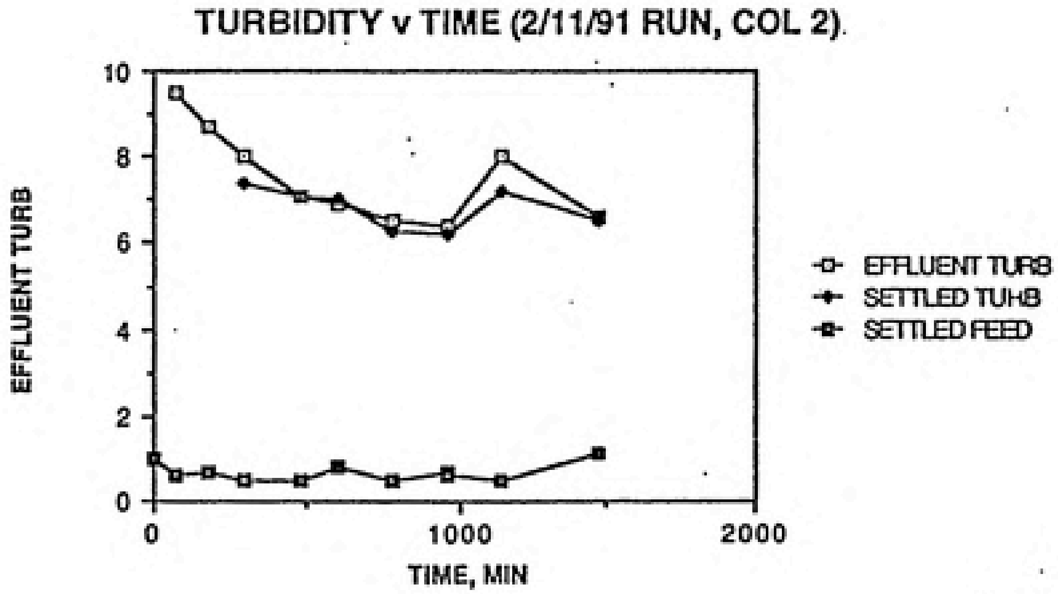
TURBIDITY v TIME (2/11/91 RUN, COL 1)
TURBIDITY, NTU
15
10
5
0
0
1000
2000
3000
4000
TIME, MIN
EFFLUENT TURB
SETTLED TURB
SETTLED FEED

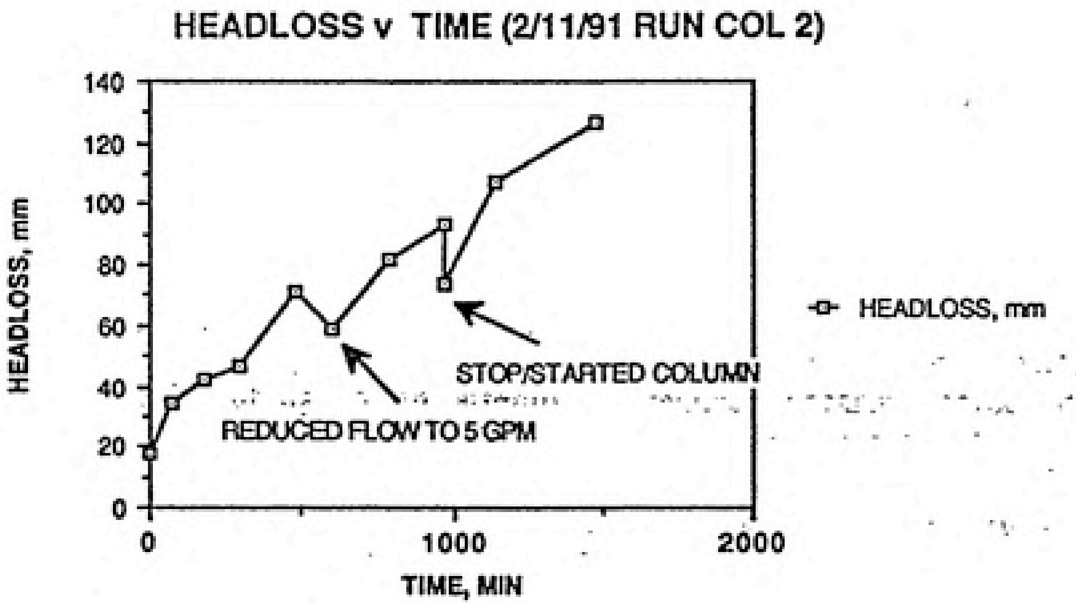


HEADLOSS v TIME (2/11/91 RUN, COL 1)
HEADLOSS, mm
100
80
60
40
20
0
0
1000
2000
3000
4000
TIME, MIN
REDUCED FLOW TO 5 GPM
HEADLOSS, mm


G VALUE v HEADLOSS (2/11/91 RUN, COL 2)
G VALUE, 1/s
TIME, MIN
70
60
50
40
30
0
1000
2000
STOP/STARTED COLUMN
REDUCED FLOW TO 5 GPM
G VALUE, 1/s


G VALUE v HEADLOSS (2/11/91 RUN, COL 2)
G VALUE, 1/s
HEADLOSS, mm
70
60
50
40
30
0
20
40
60
80
100
120
140
G VALUE, 1/s


TURBIDITY v TIME (2/11/91 RUN, COL 2)
EFFLUENT TURB
TIME, MIN
0
1000
2000
0
2
4
6
8
10
EFFLUENT TURB
SETTLED TUHB
SETTLED FEED


HEADLOSS v TIME (2/11/91 RUN COL 2)
HEADLOSS, mm
TIME, MIN
0
1000
2000
0
20
40
60
80
100
120
140
STOP/STARTED COLUMN
REDUCED FLOW TO 5 GPM
HEADLOSS, mm

Monthly Progress Report / Buoyant Coarse Media Flocculator

March, 1991

This month we made five pilot scale flocculation runs with the tapered bed at a turbidity of 20 NTU of kaolinite and at flow rates of 15 and 13 GPM. Ferric chloride was used as the coagulant in all runs; no polymer was used. The ceramic media in the bed was stratified into 1 foot 4 inches of 3/8"media, 1 foot 8 inches of 1/2 inch media, and 1 foot 7 inches of 3/4 inch media. Two tracer studies were performed on the tapered column, one with the clean bed and the other after 110 total hours of operation. The results are presented below as bullets, with supporting data attached.

- A total of five coagulation runs were performed using a media bed tapered to ~~35~~ 30 degrees without cleaning the media, so that they can be compiled into a single run. The runs began on March 8 and concluded on March 26. Operating conditions were 13-15 GPM, 20 NTU turbidity, and 14 mg/l ferric chloride. The initial run was at 15 GPM, but the flow was reduced to 13 GPM in all subsequent runs in order to extend the duration of each run. Overall headloss built from 19 to 260 mm. Effluent turbidities out of the flocculator ranged from 7 to 19 NTU, with most falling in the 10 to 14 NTU range. Twenty minute settled turbidities were initially in the 8 to 10 NTU range, but in the final day of the run were in the 4 to 6 NTU range. It should also be noted that the flocs from the current tapered bed configuration were larger than those which were achieved in the straight vertical bed configuration. It appeared that the improved settled turbidities were the result of ripening of the bed, the tapered and stratified bed configuration, and improved sampling technique. In addition, water temperature increased from 11.5° to 16.5° C over the course of the month.

- Sampling from the bottom of the flocculator was performed with 1-1/4" tubing in an attempt to reduced shearing forces during samping. The larger size of the tubing did achieve the goal of reducing floc shearing while sampling; however, controlling flow during sampling became extremely difficult. If the flow in the sample tubing was not strictly controlled, it could induce a pulse through the bed resulting in the release of excessive amounts of deposited floc from within the bed. These released floc were large and settled quite readily.

- The discharge from the flocculator was modified by inserting a piece of PVC pipe into the effluent line. Numerous holes had been drilled into the pipe to direct flow and eliminate circuitous flow patterns below the media bed which were detected during tracer studies.

- Two tracer studies were run this month, one while the tapered bed was still clean and the other after the bed had ripened. The initial mean residence time was 167 seconds; after 110 hours, the mean residence time was 90 seconds. The average dirty bed porosity was calculated to be 0.22, compared to the average clean bed porosity of 0.40. During the initial tracer study, the clean bed headloss was 19 mm. The headloss was 235 mm during the second tracer study.

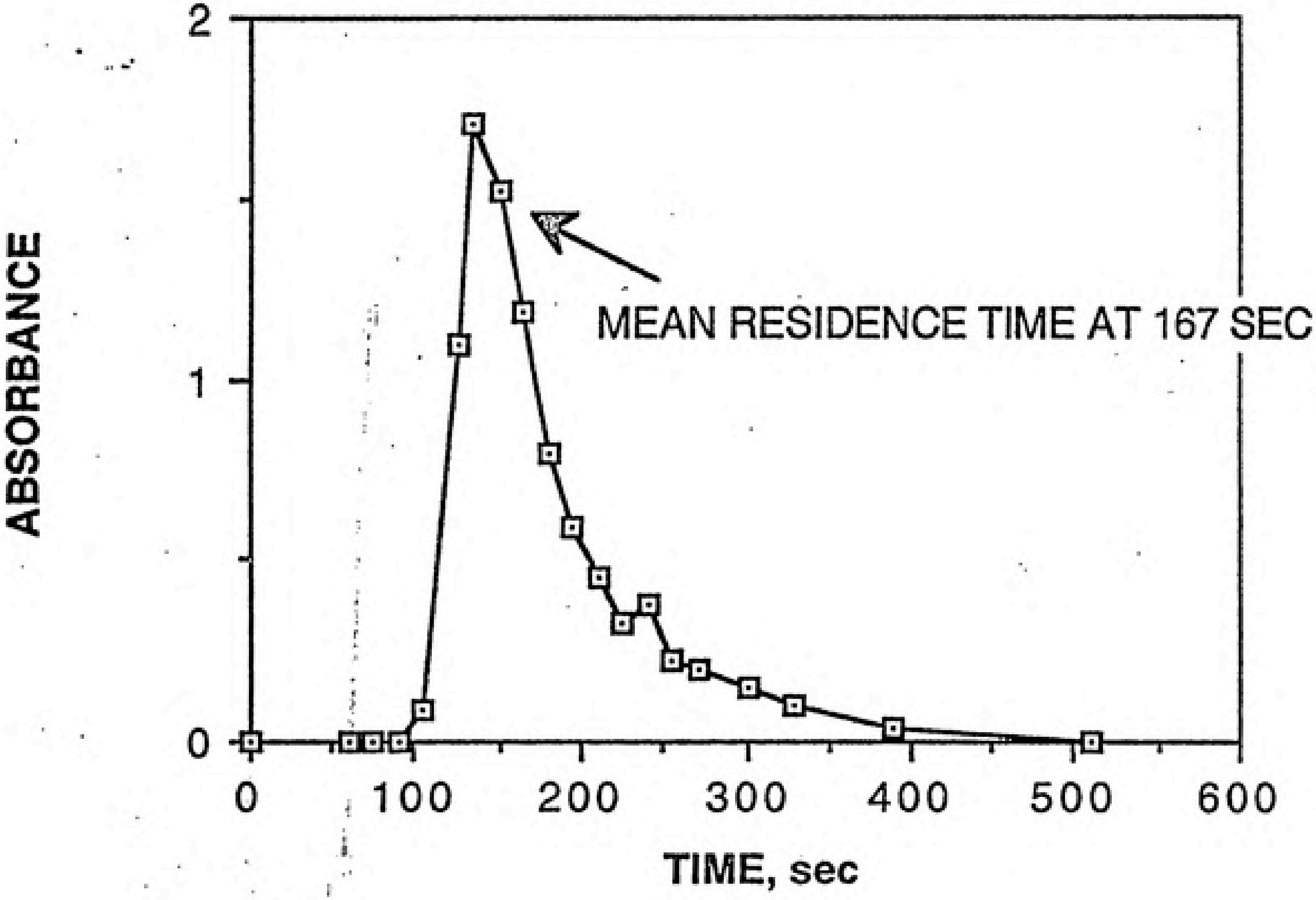
In summary, the tapered bed seemed to give better results than the straight column, though the improvement was modest. Sampling technique is a critical aspect in evaluating the performance of the flocculator.

Plans for April:

The tapered bed will be run with ferric chloride and polymer after optimal doses have been determined by jar tests. The purpose of adding the polymer will be to increase floc strength. Several runs will also be made at different feed water turbidities, e.g. 5 and 200 NTU, to evaluate performance as a function of influent turbidity. Improvements in sampling through the 1-1/4" tubing will be attempted by drilling a hole in the bottom of a settling jar and glueing a valve into the hole. The tubing will be connected to the valve so that the flow feeds directly into the bottom of the jar without the vertical drop into the jar which induces shearing of flocs.

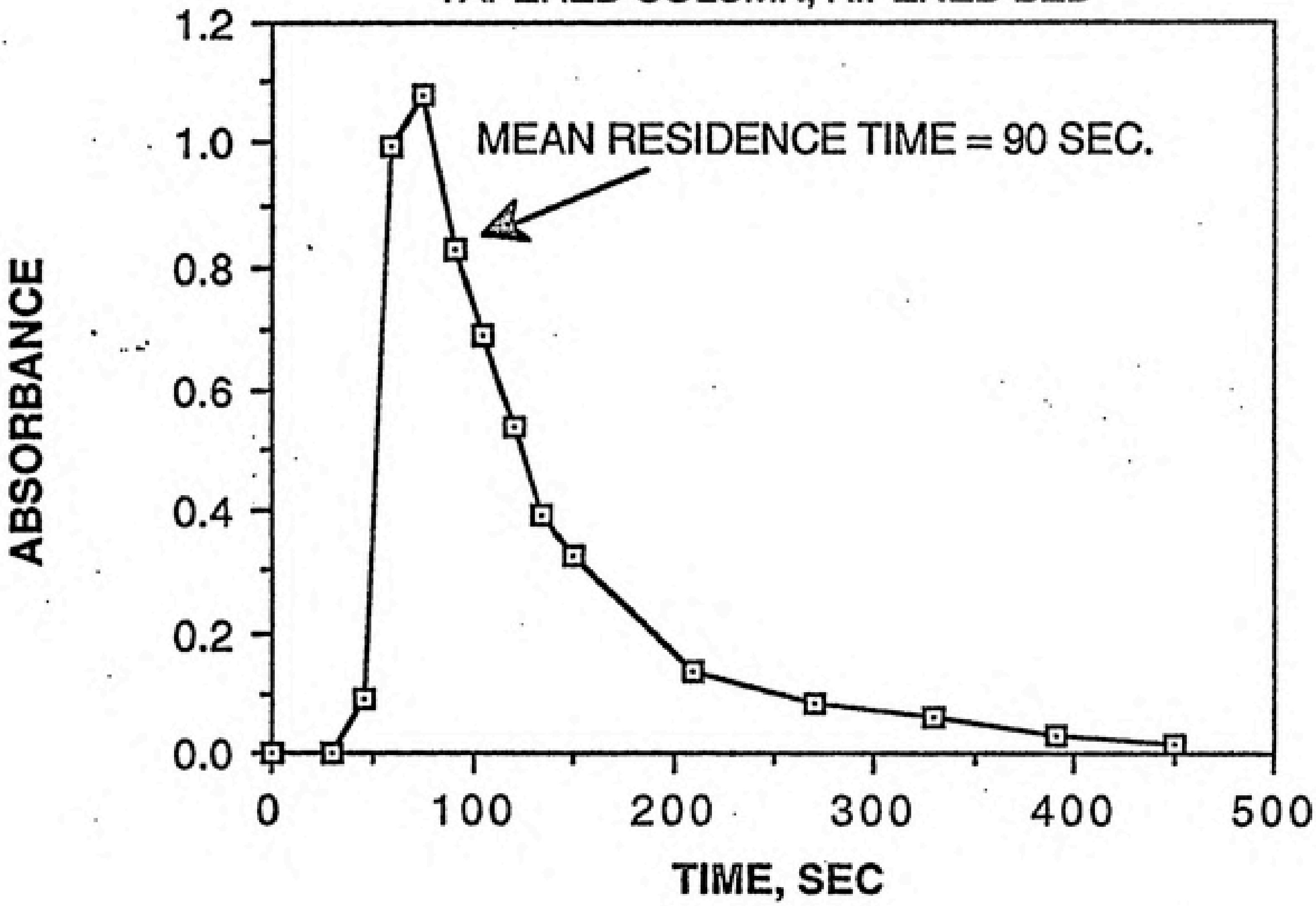
TRACER STUDY (3/6/91)

TAPERED COLUMN; CLEAN BED



TRACER STUDY (4/3/91)

TAPERED COLUMN; RIPENED BED



Jartest Date: 03/08/91

Jar test for coagulation run #11

Water: Water from outside tanks
Temp.: 11.6 C
Coagulant: $FeCl_3$
Turbidity: 20 NTU as Kaolinite
Alkalinity: $NaHCO_3$ 42 mg/l additional

Jar	1	2	3	4	5	6
Parameter						
FeCl3,mg/l	10	11	12	13	14	15
Poly/mg/l	0.0	0.0	0.0	0.0	0.0	0.0
Init. pH	7.6	7.6	7.6	7.6	7.6	7.6
Init.Turb	21.0	20.0	21.0	20.0	21.0	21.0
Removal						
5 min	4.3	3.0	3.5	2.3	2.7	2.0
20 min	1.9	1.4	0.8	0.9	0.7	0.7
removal/%	91.0	93.0	96.2	95.5	96.7	96.7
pH			6.60		6.70	

Remarks
Jar test indicates that 12-15 mg/l is an acceptable $FeCl_3$ dosage
Rapid mix for two minutes
Tapered flocculation of :
5 min at 60 RPM
5 min at 30 RPM
5 min at 15 RPM

COAGULATION RUN #11 03/08/91

FEED WATER CHARACTERISTICS:

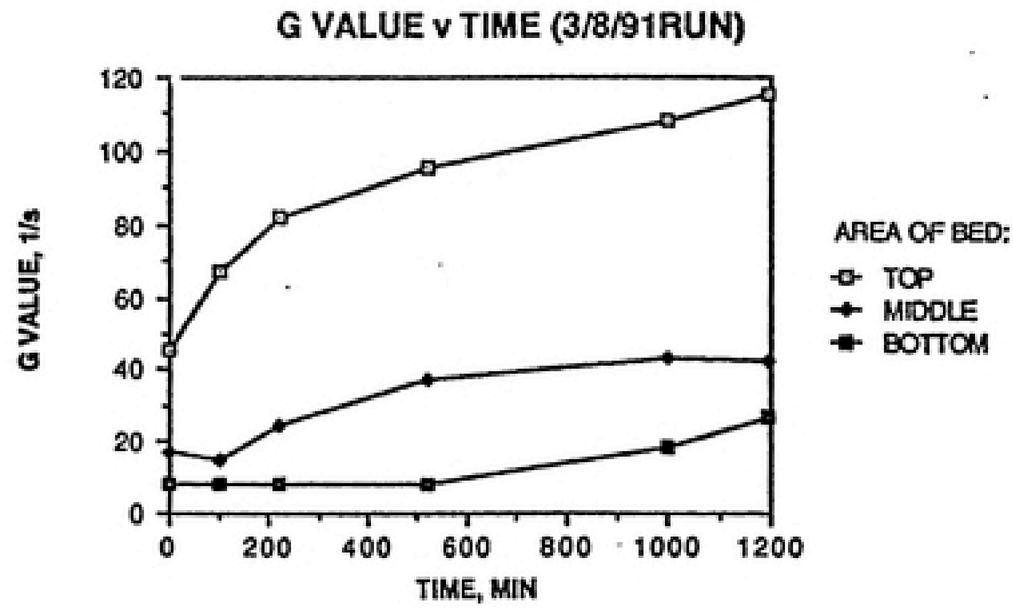
Turbidity:	20 NTU
Coagula : FeCl	14 mg/l
Polymer:	0 mg/l
Alkalinity: NaHCO3	42 mg/l
Raw wat pH with FeCl	6.5-6.7
Temperature:	11.6 C

Media:			
3/8 " 3M	B.-Height	1.33 '	Downflow
1/2 " 3M	B.-Height	1.67 '	Downflow
3/4" 3M	B.-Height	1.58 '	Downflow

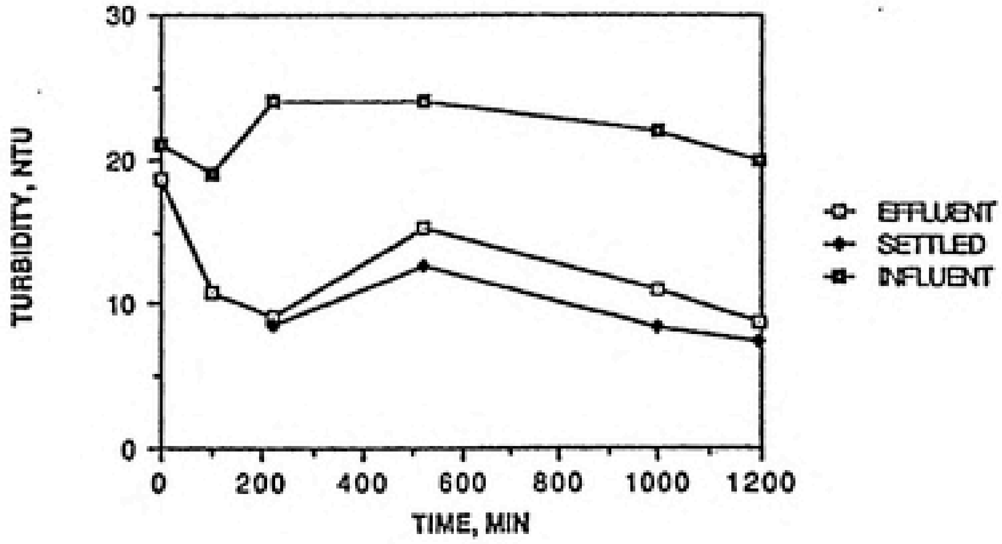
SAMPLE #	TIME min	HEADLOSS: TOP mr	MID PT mm	O'ALL mm	G-VALUE: TOP 1/s	MID POINT 1/s	BOTTOM 1/s	3M MEDIA: TURBIDITY,NTU EFFLUENT	SETTLED	FEED SETTLED	INT. TURB.
1	0.0	14	18	19	45.2	17.5	8.4	18.6		1.2	21.0
2	100.0	31	34	35	67.3	15.1	8.4	10.8		0.9	19.0
3	220.0	46	54	55	82.0	24.7	8.4	9.1	8.5	1.2	24.0
4	520.0	62	80	81	95.2	37.0	8.4	15.3	12.7	0.8	24.0
5	1000.0	80	105	110	108.1	43.6	18.9	11.0	8.4	0.9	22.0
6	1195.0	92	116	126	115.9	42.8	26.7	8.8	7.4	0.6	20.0

Remarks:

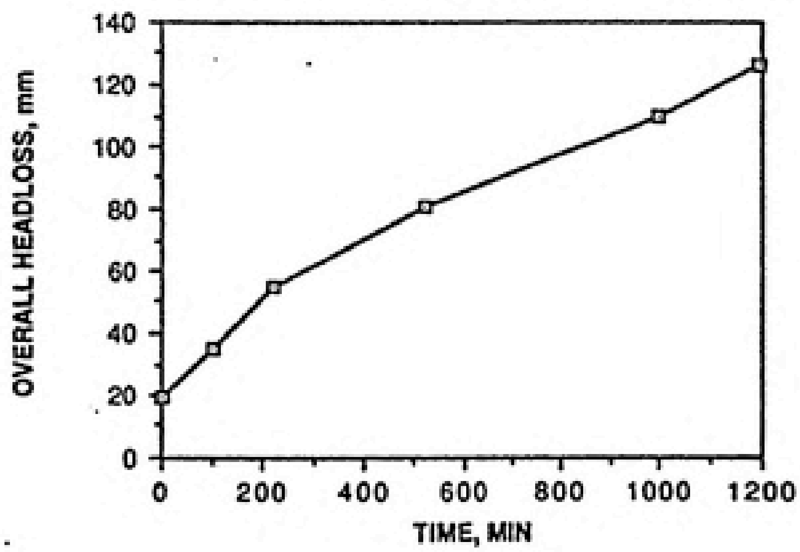
1. This and the subsequent 4 runs are designed to test the effect of tapering the media bed.


G VALUE v TIME (3/8/91RUN)
G VALUE, 1/s
TIME, MIN
0
20
40
60
80
100
120
0
200
400
600
800
1000
1200
AREA OF BED:
TOP
MIDDLE
BOTTOM

TURBIDITY v TIME (3/8/91 RUN)



OVERALL HEADLOSS v TIME (3/8/91 RUN)



Jartest Date: 03/10/91

Jar test for coagulation run #12

Water:	Water from outside tanks
Temp.:	13.0C
Coagulant:	$FeCl_3$
Turbidity:	20 NTU as Kaolinite
Alkalinity: $NaHCO_3$	42 mg/l additional

Jar	1	2	3	4	5	6
Parameter						
$FeCl_3$,mg/l		11	12	13	14	15
Poly/mg/l		0.0	0.0	0.0	0.0	0.0
Init. pH		7.4	7.4	7.4	7.4	7.4
Init.Turb		20.0	21.0	20.0	20.0	21.0
Removal						
5 min		2.1	1.5	1.3	2.3	2.4
20 min		0.6	0.5	0.3	0.4	0.6
removal/%		97.0	97.6	98.5	98.0	97.1
pH				6.60		6.60

Remarks

Jar test indicates that 13-14 mg/l is an acceptable $FeCl_3$ dosage
Did not use jar #1 for test so that it could be used for chemistry check while starting flocculator.
Rapid mix for two minutes
Tapered flocculation of :
5 min at 60 RPM
5 min at 30 RPM
5 min at 15 RPM

COAGULATION RUN #12 03/10/91

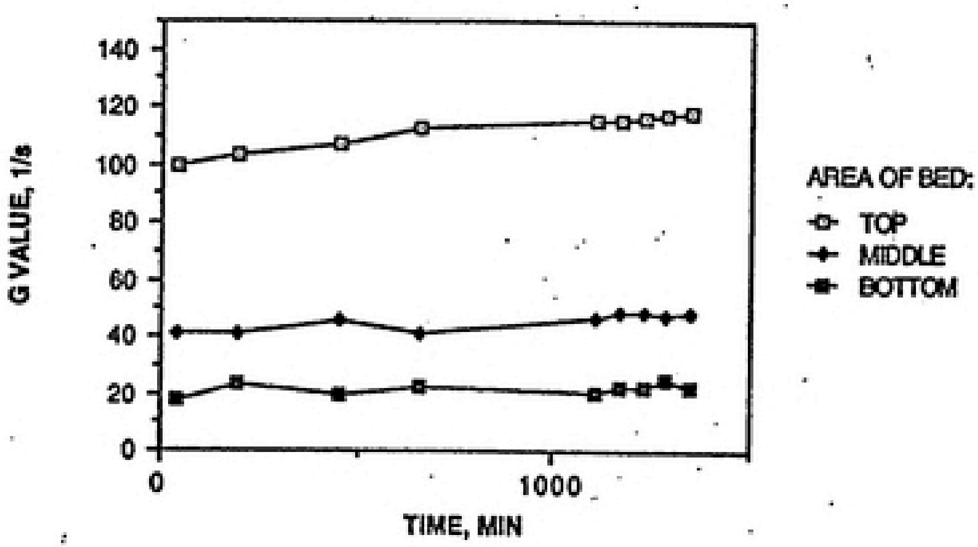
FEED WATER CHARACTERISTICS:

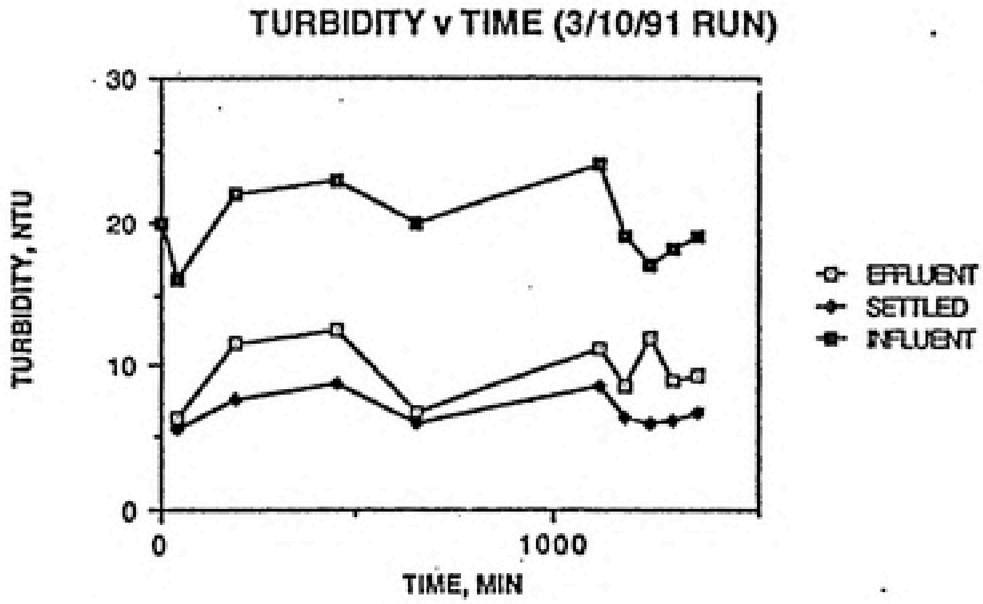
Turbidity:	20 NTU
Coagula : FeCl	14 mg/l
Polymer:	C mg/l
Alkalinity: NaHCO3	42 mg/l
Raw wat pH with FeCl	6.5-6.7
Temperature:	13.0 C

Media:			
3/8 " 3M	B.-Height	1.33 '	Downflow
1/2 " 3M	B.-Height	1.67 '	Downflow
3/4" 3M	B.-Height	1.58 '	Downflow

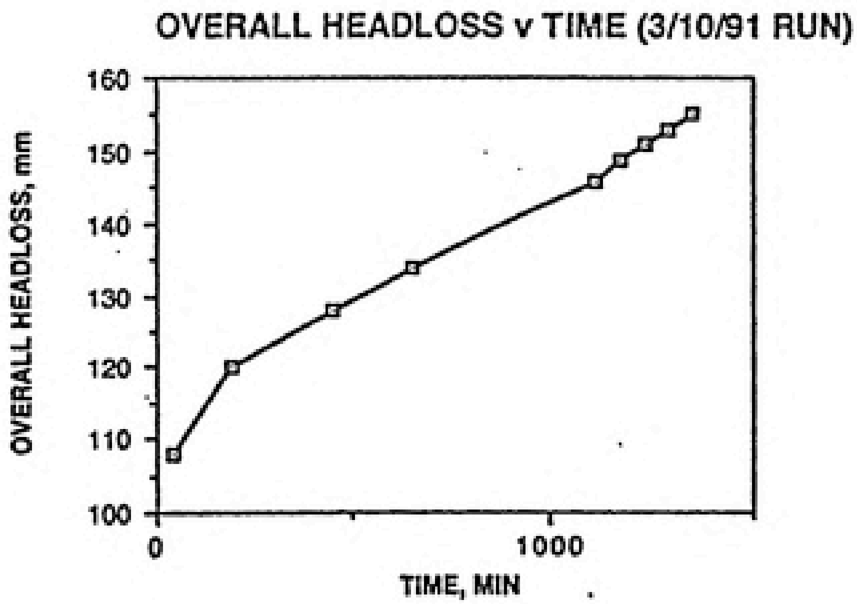
SAMPLE #	TIME min	HEADLOSS: TOP mm	MID PT mm	O'ALL mm	G-VALUE: TOP 1/s	MID PT 1/s	BOTTOM 1/s	3M MEDIA: TURBIDITY,NTU EFFLUENT	SETTLED	FEED SETTLED	INT TURB
0	0									0.7	20
1	40	78	103	108	99.4	40.6	17.5	6.4	5.5	0.6	16
2	195	85	111	120	103.7	41.4	23.5	11.5	7.7	0.6	22
3	450	91	122	128	107.3	45.2	19.2	12.5	8.8	0.6	23
4	660	101	126	134	113.1	40.6	22.2	6.7	6.0	0.6	20
5	1110	106	139	146	115.9	46.7	20.8	11.2	8.5	0.4	24
6	1170	106	141	149	115.9	48.1	22.2	8.6	6.3	0.5	19
7	1230	107	143	151	116.4	48.8	22.2	12.0	6.0	0.5	17
8	1290	109	143	153	117.5	47.4	24.8	9.0	6.2	0.5	18
9	1350	111	147	155	118.6	48.8	22.2	9.3	6.8	0.4	19

G VALUE v TIME (3/10/91 RUN)





TURBIDITY v TIME (3/10/91 RUN)
TURBIDITY, NTU
0
10
20
30
0
1000
TIME, MIN
EFFLUENT
SETTLED
INFLUENT



OVERALL HEADLOSS v TIME (3/10/91 RUN)
OVERALL HEADLOSS, mm
100
110
120
130
140
150
160
0
1000
TIME, MIN

COAGULATION RUN #13 03/19/91

FEED WATER CHARACTERISTICS:

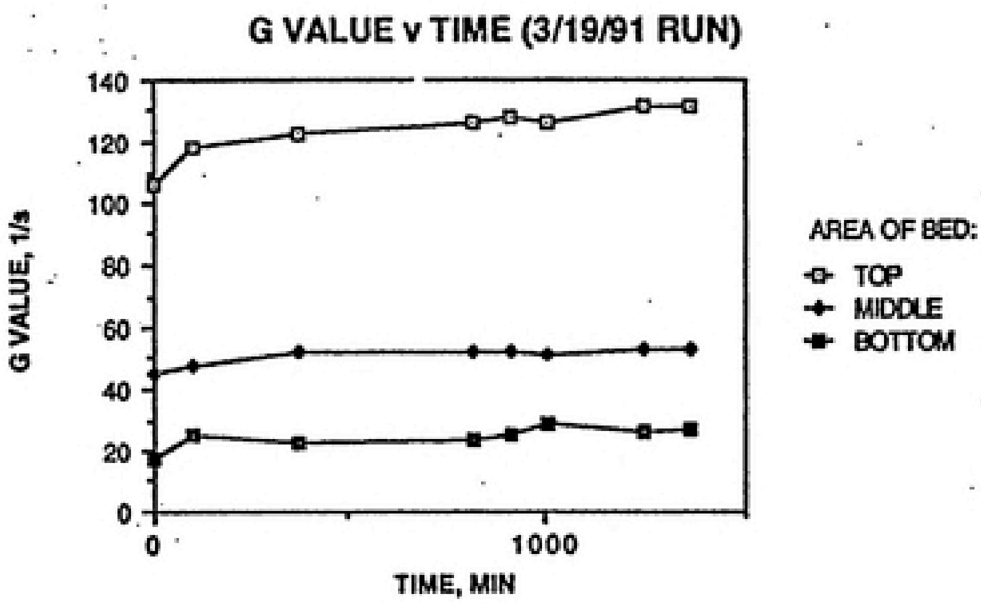
Turbidity:	20	NTU
Coagular: FeCl	14	mg/l
Polymer:	0	mg/l
Alkalinity: NaHCO3	42	mg/l
Raw wat- pH with FeCl	6.5-6.7	
Temperature:	13.5 C	

Media:	3/8 " 3M	B.-Height	1.33 '	Downflow
	1/2 " 3M	B.-Height	1.67 '	Downflow
	3/4" 3M	B.-Height	1.58 '	Downflow

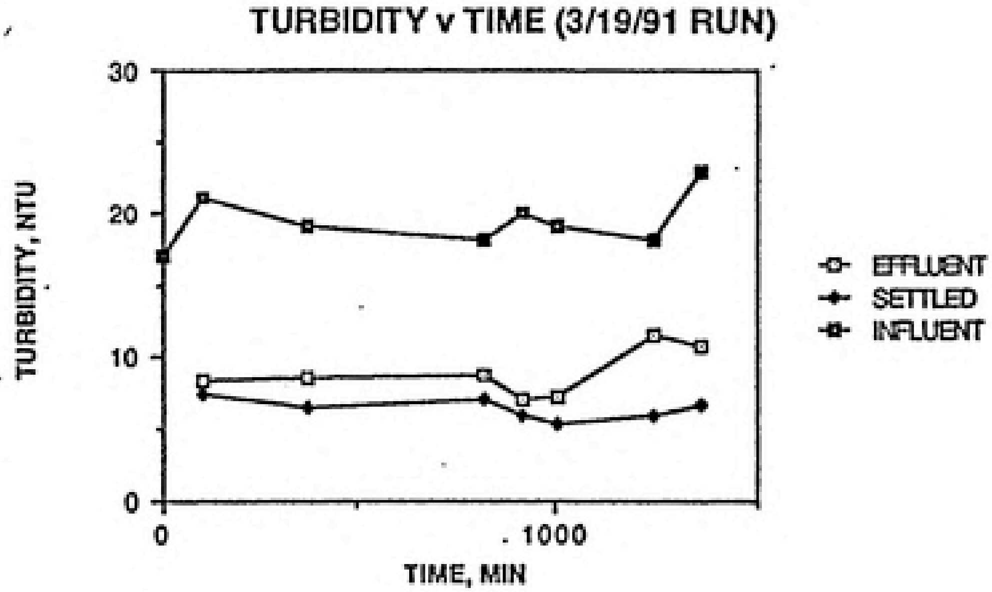
		HEADLOSS:			G-VALUE:			3M MEDIA:			
SAMPLE	TIME	TOP	MID PT	O'ALL	TOP	MID PT	BOTTOM	TURBIDITY,NTU		FEED	INT
#	min	mm	mm	mm	1/s	1/s	1/s	EFFLUENT	SETTLED	SETTLED	TURB
0	0	89	120	125	106.2	45.2	17.5			0.9	17
1	105	111	146	156	118.6	48.1	24.8	8.3	7.5	0.6	21
2	375	118	159	167	122.2	52.0	22.2	8.5	6.6	0.7	19
3	825	126	167	176	126.3	52.0	23.5	8.7	7.1	0.7	18
4	915	129	170	180	127.8	52.0	24.8	7.1	6.0	0.6	20
5	1005	126	166	179	126.3	51.4	28.3	7.3	5.4	0.7	19
6	1245	137	179	190	131.7	52.7	26.0	11.6	6.0	0.6	18
7	1365	137	180	192	131.7	53.3	27.2	10.8	6.7	0.6	23

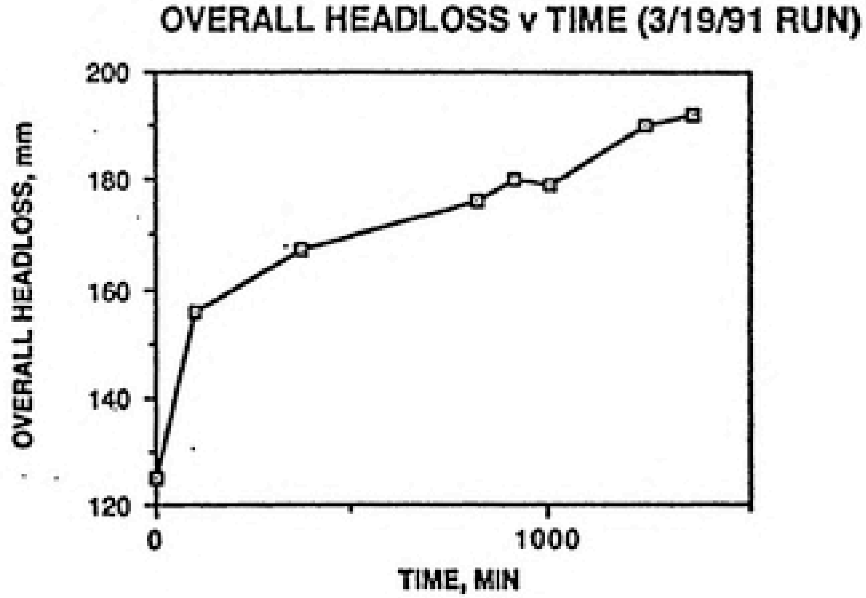
Remarks:

1. Had difficulty controlling flow from effluent sample port while purging line for sample#4. Subsequent sample was highly turbid. Took effluent sample from small tubing at bottom of bed. Overall headloss after taking sample was 159mm.



G VALUE v TIME (3/19/91 RUN)
G VALUE, 1/s
140
120
100
80
60
40
20
0
0
1000
TIME, MIN
AREA OF BED:
TOP
MIDDLE
BOTTOM


TURBIDITY v TIME (3/19/91 RUN)
TURBIDITY, NTU
30
20
10
0
0
1000
TIME, MIN
EFFLUENT
SETTLED
INFLUENT


OVERALL HEADLOSS v TIME (3/19/91 RUN)
OVERALL HEADLOSS, mm
200
180
160
140
120
0
1000
TIME, MIN

COAGULATION RUN #14 03/21/91

FEED WATER CHARACTERISTICS:

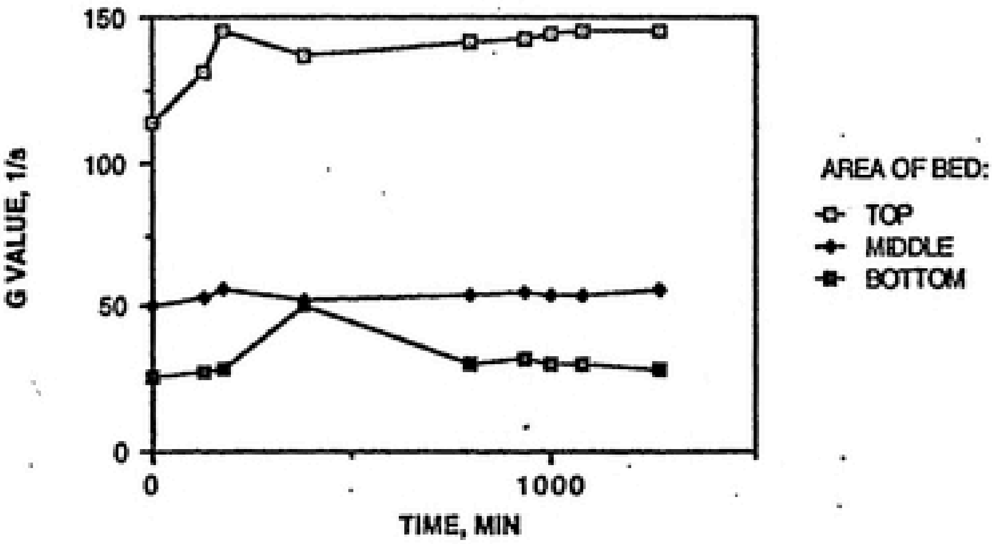
Turbidity:	20 NTU
Coagulai: FeCl	14 mg/l
Polymer:	0 mg/l
Alkalinity: NaHCO3	42 mg/l
Raw wat pH with FeCl	6.5-6.7
Temperature:	13.5 C

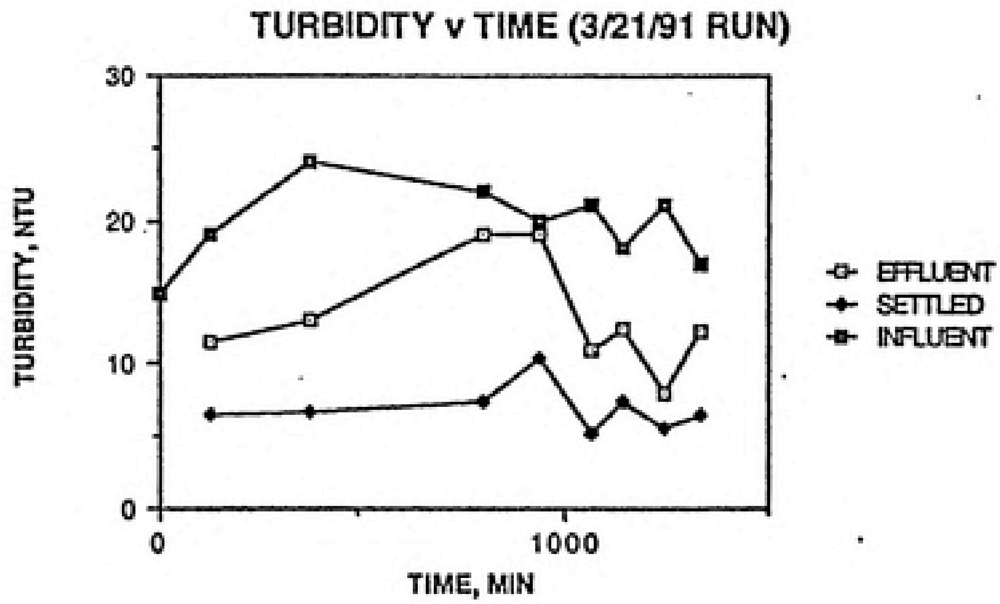
Media:	5/8 " 3M	B.-Height	1.33 '	Downflow
	1/2 " 3M	B.-Height	1.67 '	Downflow
	3/4" 3M	B.-Height	1.58 '	Downflow

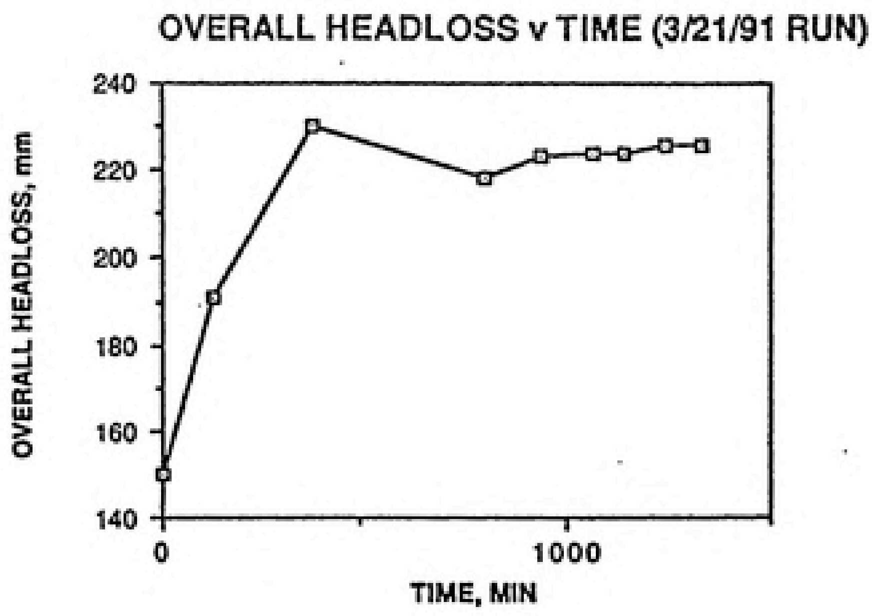
		HEADLOSS:			G-VALUE:			3M MEDIA:			
SAMPLE	TIME	TOP	MID PT	O'ALL	TOP	MID PT	BOTTOM	TURBIDITY,NTU		FEED	INT
#	min	mm	mm	mm	1/s	1/s	1/s	EFFLUENT	SETTLED	SETTLED	TURB
0	0	102	140	150	113.6	50.1	24.8			0.5	15
1	130	137	179	191	131.7	52.7	27.2	11.5	6.5	0.5	19
2	385	148	189	230	136.9	52.0	50.3	13.0	6.8	0.7	24
3	800	159	204	218	141.9	54.5	29.4	19.0	7.5	0.6	22
4	940	161	207	223	142.8	55.1	31.4	19.0	10.5	0.4	20
5	1000	165	210	224	144.5	54.5	29.4	11.0	5.3	0.4	21
6	1075	166	210	224	145.0	53.9	29.4	12.5	7.4	0.4	18
7	180	166	213	226	145.0	55.7	28.3	8.0	5.5	0.4	21
8	1270	166	213	226	145.0	55.7	28.3	12.3	6.5	0.5	17

Remarks:

G VALUE v TIME (3/21/91 RUN)




TURBIDITY v TIME (3/21/91 RUN)
TURBIDITY, NTU
30
20
10
0
0
1000
TIME, MIN
EFFLUENT
SETTLED
INFLUENT


OVERALL HEADLOSS v TIME (3/21/91 RUN)
OVERALL HEADLOSS, mm
240
220
200
180
160
140
0
1000
TIME, MIN

Jartest Date: 03/26/91

Jar test for coagulation run #15

Water:	Water from outside tanks	
Temp.:	17.2C	
Coagulant:	FeCl3	
Turbidity:	20 NTU	as Kaolinite
Alkalinity: NaHCO3	42 mg/l	additional

Jar	1	2	3	4	5	6
Parameter						
FeCl3,mg/l	10	11	12	13	14	15
Poly/mg/l	0.0	0.0	0.0	0.0	0.0	0.0
Init. pH	7.0				7.0	
Init.Turb	17.0	18.0	17.0	17.0	19.0	17.0
Removal						
5 min	1.1	1.6	1.7	1.0	1.3	1.4
20 min	0.6	0.4	0.4	0.3	0.4	0.5
removal/%	96.5	97.8	97.6	98.2	97.9	97.1
pH	6.70	6.70	6.65	6.70	6.70	6.65

Remarks
Jar test indicates that 13-14 mg/l is an acceptable FeCl3 dosage
Rapid mix for two minutes
Tapered flocculation of :
5 min at 60 RPM
5 min at 30 RPM
5 min at 15 RPM

COAGULATION RUN #15 03/26/91

FEED WATER CHARACTERISTICS:

Turbidity:	20 NTU
Coagular: FeCl	14 mg/l
Polymer:	0 mg/l
Alkalinity: $NaHCO_3$	42 mg/l
Raw wat pH with FeCl	6.5-6.7
Temperature:	16.5 C

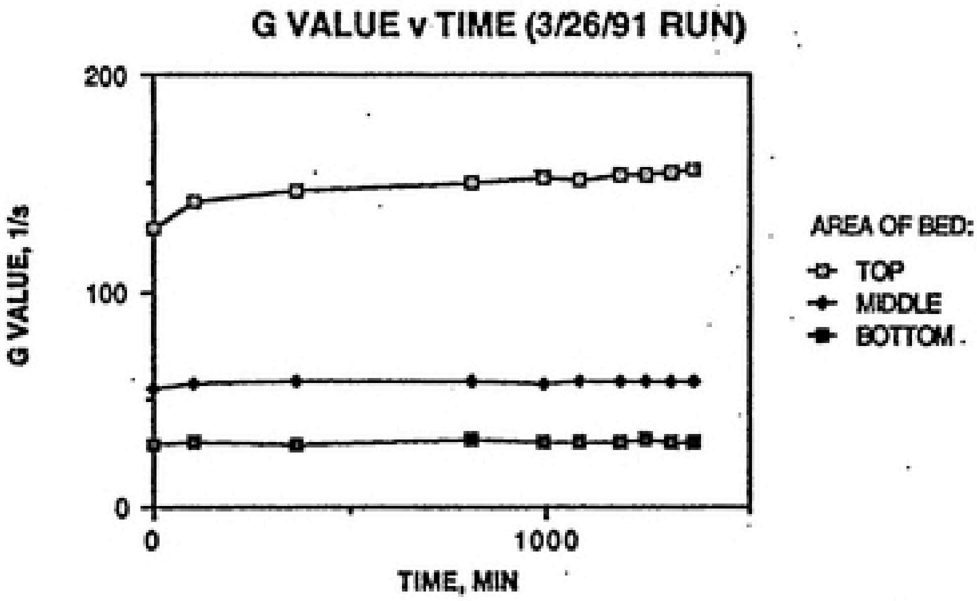
Media:	3/8 " 3M	B.-Height	1.33 '	Downflow
	1/2 " 3M	B.-Height	1.67 '	Downflow
	3/4" 3M	B.-Height	1.58 '	Downflow

		HEADLOSS:			G-VALUE:			3M MEDIA:			
SAMPLE	TIME	TOP	MID PT	O'ALL	TOP	MID PT	BOTTOM	TURBIDITY,NTU		FEED	INT
#	min	mm	mm	mm	1/s	1/s	1/s	EFFLUENT	SETTLED	SETTLED	TURB
0	0	132	177	190	129.3	54.5	28.3			0.7	16
1	105	157	206	220	141.0	56.9	29.4	14.0	8.0	0.7	21
2	365	169	220	233	146.3	58.0	28.3	13.5	6.7	0.6	26
3	810	177	228	244	149.7	58.0	31.4	11.5	5.5	0.5	20
4	990	185	234	249	153.1	56.9	30.4	14.5	6.3	0.4	20
5	1080	182	233	247	151.8	58.0	29.4	10.7	3.8	0.4	18
6	1185	186	238	253	153.5	58.6	30.4	12.8	5.0	0.5	18
7	1245	187	239	255	153.9	58.6	31.4	15.0	5.3	0.6	18
8	1305	190	241	255	155.1	58.0	29.4	13.0	4.2	0.6	18
9	1365	193	245	260	156.3	58.6	30.4	10.0	4.2	0.5	21

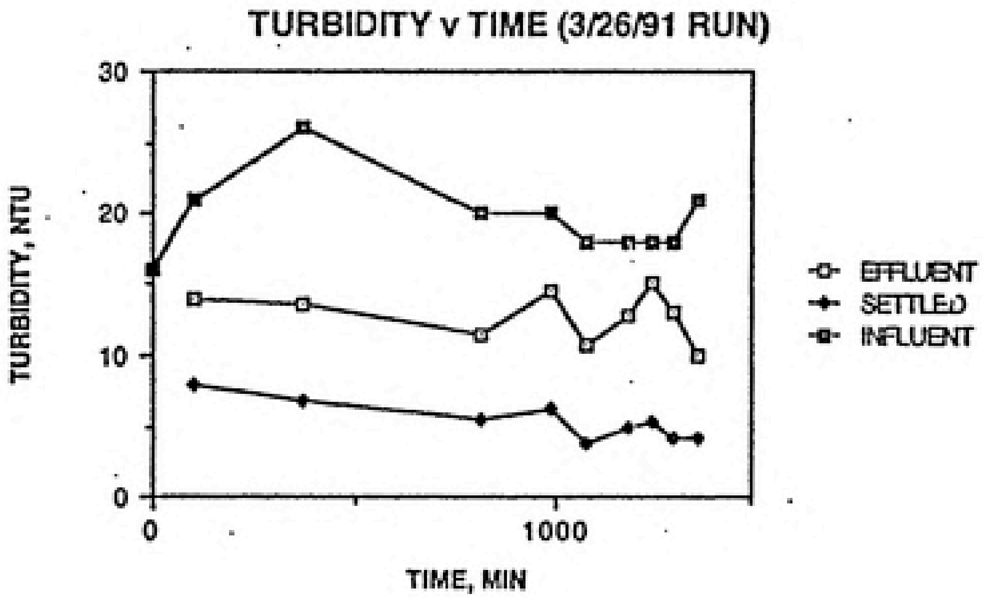
Remarks:

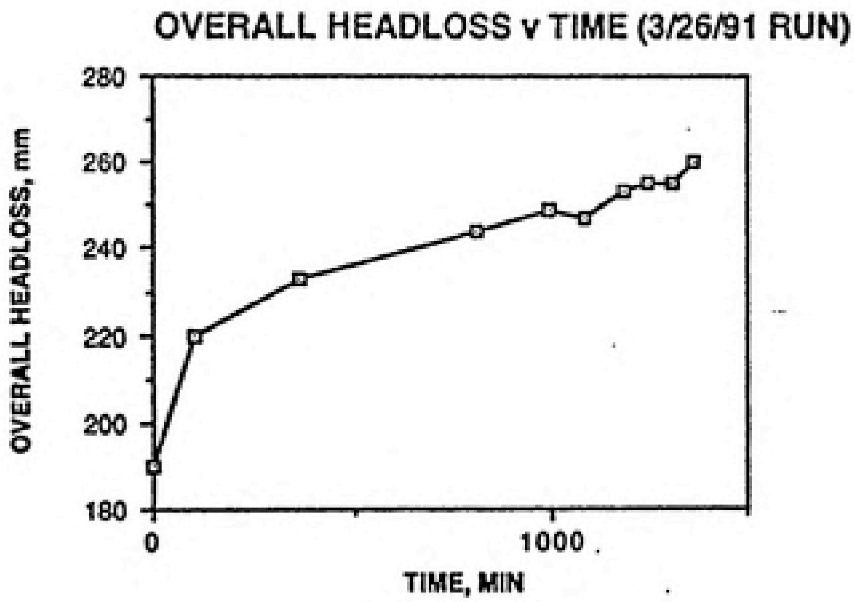
1. Influent turbidity was high because clay tank was nearly empty.
2. Samples #3 and 5 were taken from small tubing at bottom of bed.
3. For comparitive purposes sample #4 was taken from both small and large tubing. The following results were obtained:

Tubing	Effluent	Settled
Large	14.5	6.3
Small	9.0	4.4

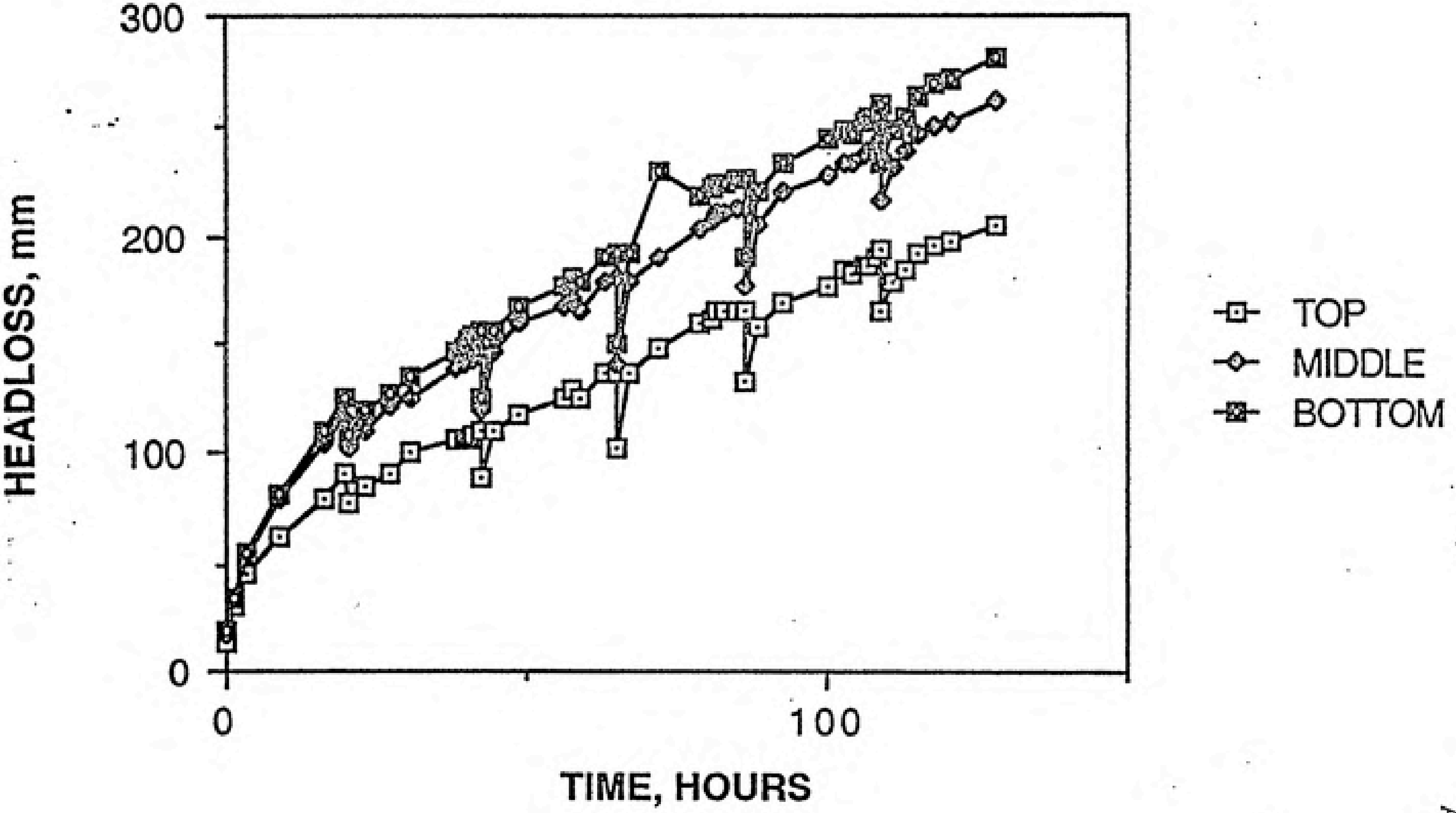


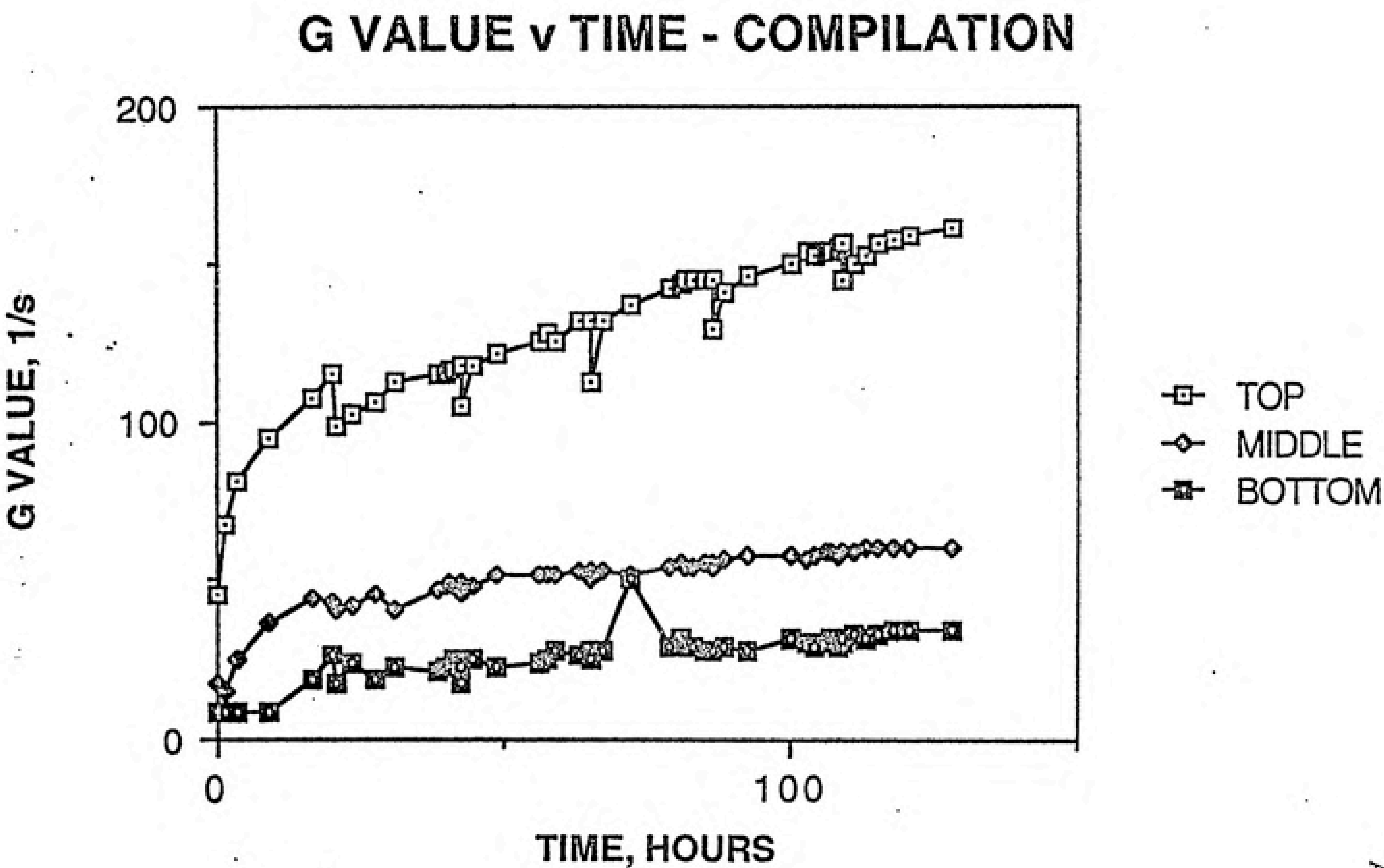
G VALUE v TIME (3/26/91 RUN)
200
100
0
G VALUE, 1/s
0
1000
TIME, MIN
AREA OF BED:
TOP
MIDDLE
BOTTOM

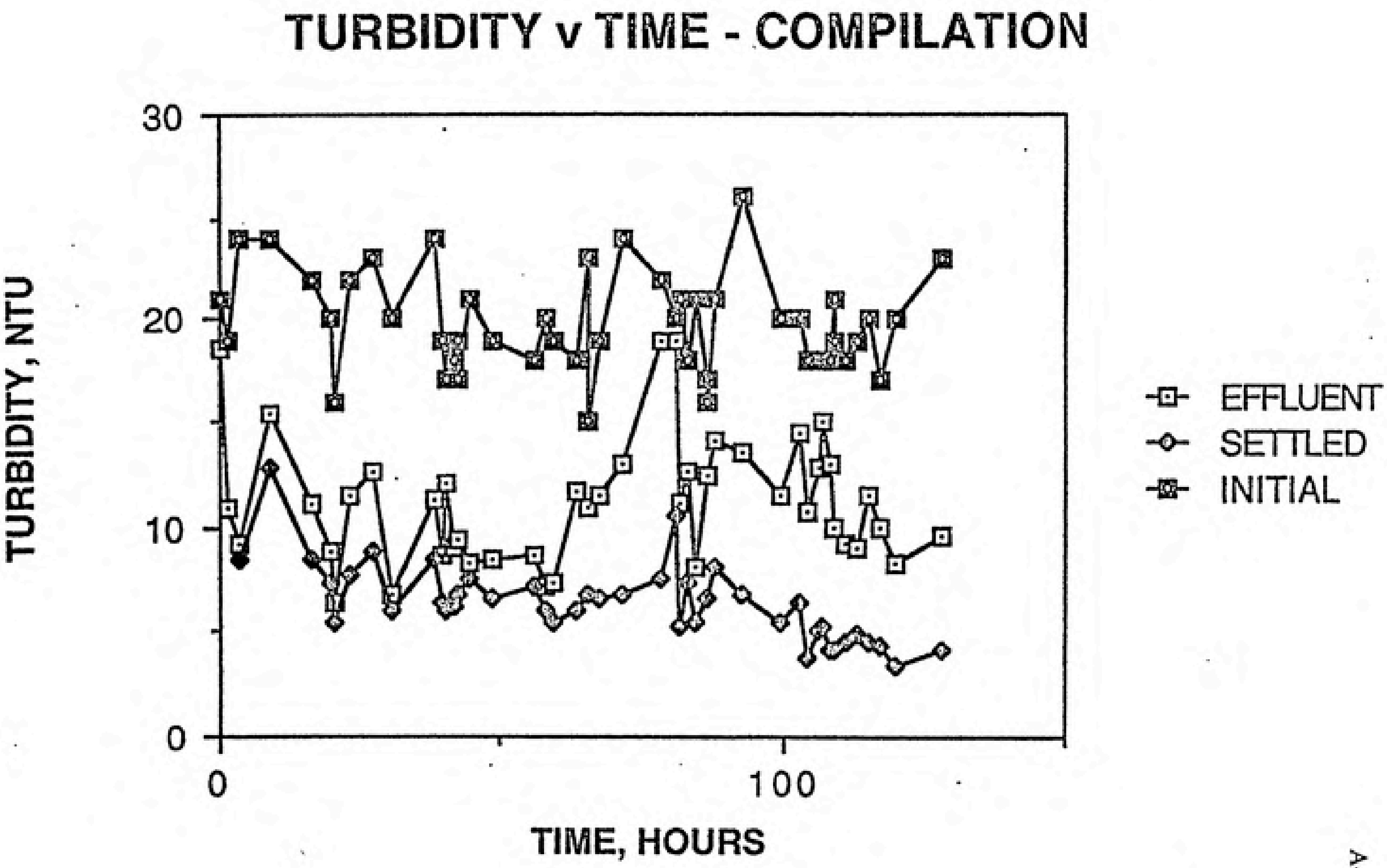

TURBIDITY v TIME (3/26/91 RUN)
30
20
10
0
TURBIDITY, NTU
0
1000
TIME, MIN
EFFLUENT
SETTLED
INFLUENT


OVERALL HEADLOSS v TIME (3/26/91 RUN)
280
260
240
220
200
180
OVERALL HEADLOSS, mm
0
1000
TIME, MIN

HEADLOSS v TIME - COMPILATION




G VALUE v TIME - COMPILATION
200
100
0
G VALUE, 1/s
0
100
TIME, HOURS
TOP
MIDDLE
BOTTOM


TURBIDITY v TIME - COMPILATION
30
20
10
0
TURBIDITY, NTU
0
100
TIME, HOURS
EFFLUENT
SETTLED
INITIAL

MEMORANDUM

TO: Chris Schultz, Hollie Scott

FROM: Philip C. Singer

DATE: May 22, 1991

SUBJECT: April/May Progress Report on Buoyant Coarse Media Flocculation Project

Attached is a copy of our progress report covering the period April 1 to May 15, 1991. You should note that, while we have been unable to achieve settled water turbidities of less than 2 NTU in the flocculator (except when the raw water turbidity was 5 NTU), we were able to consistently achieve effluent turbidities of less than 2 NTU when we operated the overflow column as an upflow solids contactor packed with the Norpak media, even at overflow rates of 3 and 5 gpm/sq ft.

We are currently operating the tapered bed filled with the 3M tapered ceramic media over Norpak, and will continue to operate in this mode until the technical advisory group meeting on June 3. We then plan to dismantle the unit and move it to OWASA where we will run for the remainder of the project on coagulated raw University Lake water.

We look forward to meeting with you on June 3. Please call me if you have any questions.

[redacted]

Monthly Progress Report / Buoyant Coarse Media Flocculator

April 1 to May 15, 1991

This report covers one and one-half months of pilot plant work. Seven flocculation runs were made with the tapered bed filled with ceramic media as described in the March report. For three of these runs, the overflow column was filled with Norpak media. Ferric chloride was used as the coagulant; polymer was used during one of these runs. Water temperatures ranged from 19.0 to 22.0°C The results are presented below as bullets.

- Of the four runs with no media in the overflow column, one each was run at 20 and 5 NTU and the other two at 100 NTU. For the 20 NTU run of April 9, 14 mg/l of $FeCl_3$ and 0.3 mg/l of polymer were used. Flowrate was 13 GPM. Effluent turbidity averaged 9.5 NTU, settling to an average of 4.5 NTU after 20 minutes. For the 5 NTU run of April 11, 12 mg/l of $FeCl_3$ was used. Flowrate was 13 GPM. Effluent turbidity averaged 3.0 NTU, settling to 1.5 NTU. The first 100 NTU run of April 17 was used to demonstrate the tapered bed configuration and ease of cleaning the bed rather than to acquire data. Sampling intervals were therefore inconsistent and the run was repeated on April 19. For the April 19 run, conditions were 13 GPM flowrate and 18 mg/l of $FeCl_3$. Average effluent turbidity was 40 NTU, settling to 12 NTU. The flocculator was found to remove a higher percentage of influent turbidity when the influent turbidity was raised. However, only the 5 NTU influent produced an acceptable settled water turbidity (less than 2 NTU).

- The next three runs were made with 3/4" Norpak in the overflow column. During the run of April 23, the overflow column loading rate was initially 16.0 GPM/Ft^2, decreased to 2.6 GPM/Ft^2, and finally ended at 5.0 GPM/Ft^2. The column was sampled from the overflow tubing with one of the jar test jars. After the overflow column had become laden with floc, the effluent turbidity was 2.0-3.0 NTU, settling to 1.0-1.4 NTU, at the 2.6 GPM/Ft^2 overflow rate. At the 5.0 GPM/Ft^2 overflow rate, the effluent turbidity was 5.6 NTU, settling to 1.0 NTU. At the 16.0 GPM/Ft^2 overflow rate, we experienced very high effluent turbidities which nevertheless settled to an average of 4.0 NTU. Throughout the run, turbidities at the bottom of the flocculator averaged 15.0 NTU, settling to 4.5 NTU. Operating conditions for this run were 8 GPM flowrate and 14 mg/l $FeCl_3$.

- The loading rate to the overflow column during the next run was held constant at 3.0 GPM/Ft^2. The overflow sampling location was changed from the discharge tubing to taking a small sample directly from the top of the column. This change was made because it was felt that the effluent turbidity from the overflow column increased as a result of settleable floc breaking up during the drop from the column into the sampling jar. Effluent from the overflow column averaged under 2.0 NTU, settling to approximately 1.0 NTU. Turbidities from the flocculator averaged 15.0 NTU, settling to 4.5 NTU. Flowrate through the flocculator was 6.0 GPM and $FeCl_3$ dosage was 14 mg/l.

- The final run with Norpak in the overflow column was at a loading of 5.0 GPM/Ft^2. Until the Norpak became saturated with floc at 30.5 hours, the effluent from the overflow column averaged 2.5 NTU and was as low as 1.8 NTU. Settled turbidities averaged 1.5 NTU and were as low as 1.1 NTU. Effluent from the flocculator averaged 13.0 NTU, settling to an average of 4.5 NTU. These averages ignore the later effluent samples in the run when substantial floc had accumulated at the bottom of the flocculator, making sampling difficult. Flowrate through the flocculator was 6.0 GPM and $FeCl_3$ dosage was 14 mg/l.

- A new technique was used for the first time this month to sample flocculator effluent. A one inch pipe was inserted through a hole drilled in the bottom of a jar test jar. Tubing from the bottom of the flocculator was slipped over the pipe, and the jar filled from the bottom. The technique allows the jar to be filled with minimal floc breakup.

Plans for May/June:

The tapered bed will be repacked in a downflow configuration with small and medium ceramic media followed by 1" Norpak. After running this configuration at several flowrates, the pilot plant will be disassembled and moved to the OWASA water treatment plant to be run with their coagulated raw water.

Jartest Date: 04/05/91

Jar test with polymer for coagulation run #16

Water: Water from outside tanks
Temp.: 17.3C
Coagulant: $FeCl_3$
Turbidity: 20 NTU as Kaolinite
Alkalinity: $NaHCO_3$ 42 mg/l additional

Jar	1	2	3	4	5	6
Parameter						
$FeCl_3$,mg/l	12	13	14	12	13	14
Poly/mg/l	0.3	0.3	0.3	0.5	0.5	0.5
Init. pH	7.0				7.0	
Init.Turb	20.0	20.0	21.0	20.0	21.0	19.0
Removal						
5 min	0.9	1.7	1.5	1.1	0.6	0.7
20 min	0.3	0.4	0.4	0.5	0.4	0.4
removal/%	98.5	98.0	98.1	97.5	98.1	97.9
pH	6.60	6.60	6.60	6.65	6.60	6.60

Remarks
Jar test indicates that .3-.5 mg/l of polymer is superior to 0 or 0.1 mg/l of polymer.
Rapid mix for two minutes
Tapered flocculation of :
5 min at 60 RPM
5 min at 30 RPM
5 min at 15 RPM

COAGULATION RUN #16 04/09/91

FEED WATER CHARACTERISTICS:

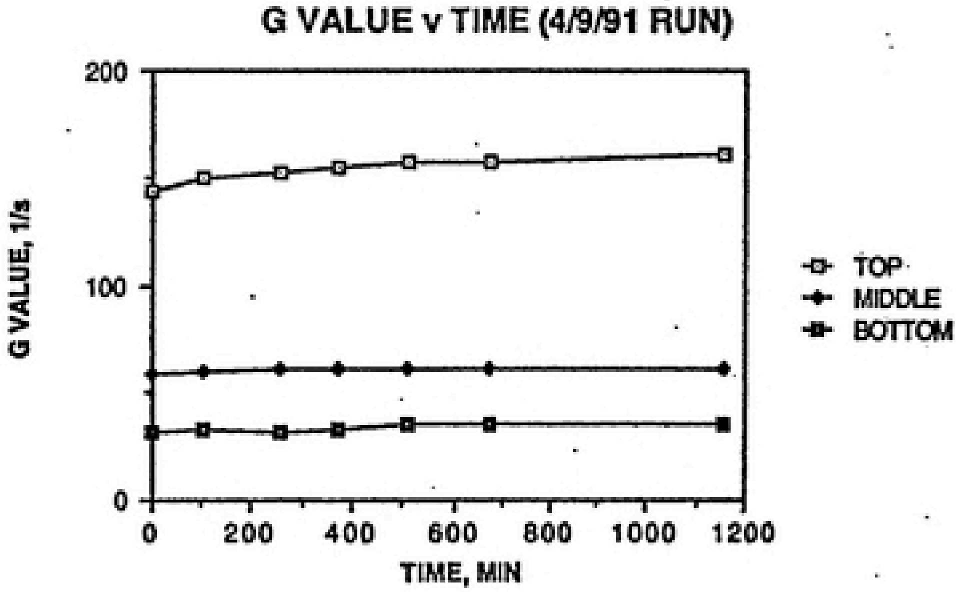
Turbidity:	20 NTU
Coagular: FeCl	14 mg/l
Polymer:	0.3 mg/l
Alkalinity: NaHCO3	42 mg/l
Temperature:	19 C
Flowrate	13 GPM

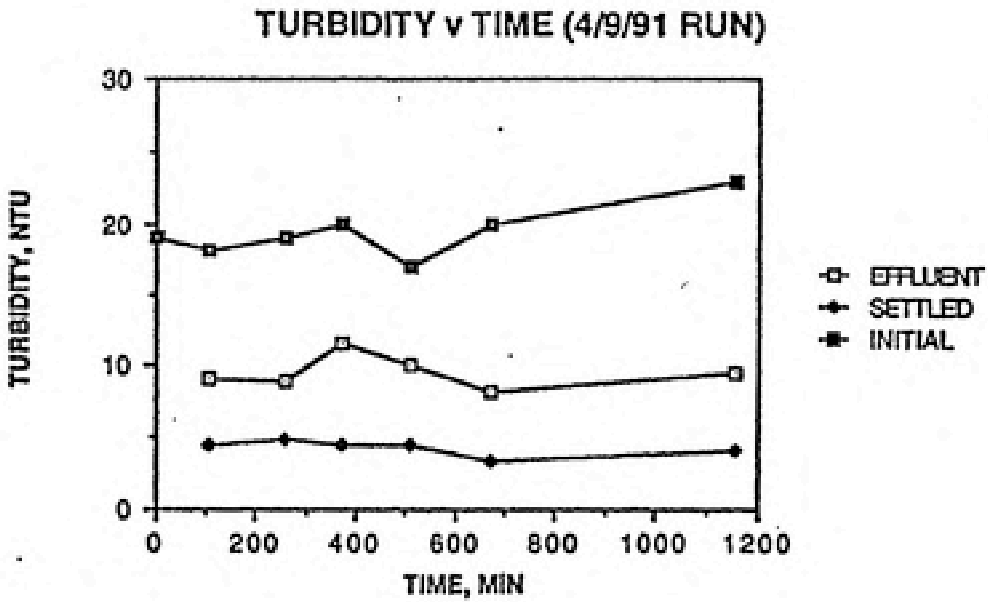
Media:	3/8 " 3M	B.-Height	1.33 '	Downflow
	1/2 " 3M	B.-Height	1.67 '	Downflow
	3/4" 3M	B.-Height	1.58 '	Downflow

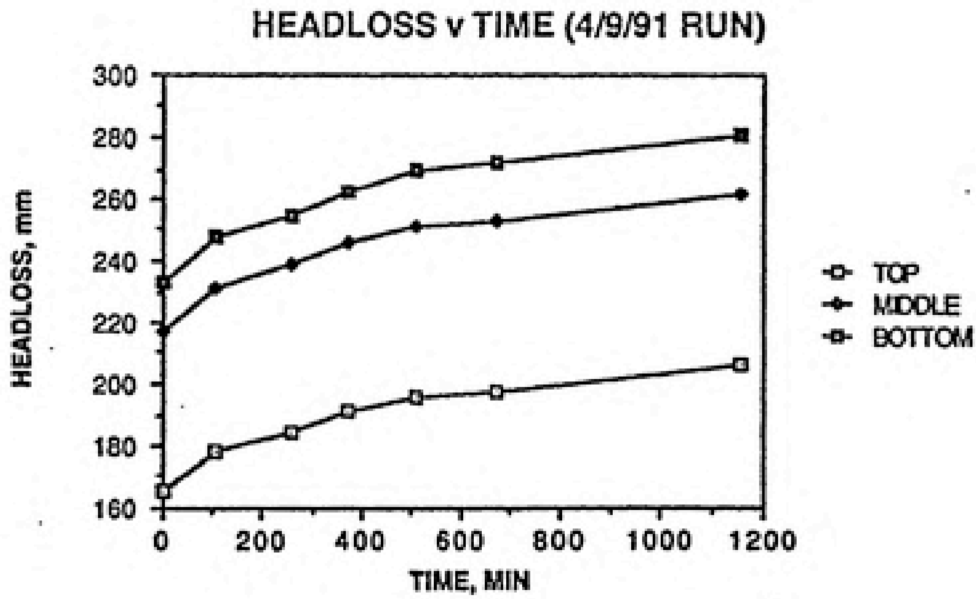
			HEADLOSS:			G-VALUE:		3M MEDIA:			
SAMPLE	TIME	TOP	MID PT	O'ALL	TOP	MID PT	BOTTOM	TURBIDITY,NTU		FEED	INT
#	min	mm	mm	mm	1/s	1/s	1/s	EFFLUENT	SETTLED	SETTLED	TURB
0	0	165	217	233	144.5	58.6	31.4			0.7	19
1	105	178	231	248	150.1	59.2	32.4	9.1	4.5	0.4	18
2	255	184	239	255	152.6	60.3	31.4	9.0	4.8	0.6	19
3	375	191	246	263	155.5	60.3	32.4	11.5	4.5	0.5	20
4	510	196	251	270	157.5	60.3	34.2	10.0	4.4	0.5	17
5	675	197	253	272	157.9	60.8	34.2	8.2	3.3	0.5	20
6	1155	206	262	281	161.5	60.8	34.2	9.5	4.1	0.5	23

Remarks:

1. This run was designed to test the effect of polymer when used with ferric chloride.
2. The samples for this run were taken using the small tubing to fill jartest jar from bottom.
3. This run was terminated when the water tanks ran dry; the bed drained approx. 1/3.
4. Effluent and settled turbidities were generally lower and more consistent than in previous runs. This could have been because of the polymer or the new sampling technique.


G VALUE v TIME (4/9/91 RUN)
G VALUE, 1/s
200
100
0
0
200
400
600
800
1000
1200
TIME, MIN
TOP
MIDDLE
BOTTOM


TURBIDITY v TIME (4/9/91 RUN)
TURBIDITY, NTU
30
20
10
0
0
200
400
600
800
1000
1200
TIME, MIN
EFFLUENT
SETTLED
INITIAL


HEADLOSS v TIME (4/9/91 RUN)
HEADLOSS, mm
300
280
260
240
220
200
180
160
0
200
400
600
800
1000
1200
TIME, MIN
TOP
MIDDLE
BOTTOM

Jartest   Date: 04/11/91

Jar test for coagulation run #17 (5 NTU)

Water:	Water from outside tanks	
Temp.:	19.0	
Coagulant:	$FeCl_3$	
Turbidity:	5 NTU	as Kaolinite
Alkalinity: $NaHCO_3$	42 mg/l	additional

Jar	1	2	3	4	5	6
Parameter						
$FeCl_3$,mg/l	0	10	11	12	13	14
Poly/mg/l	0.0	0.0	0.0	0.0	0.0	0.0
Init. pH	7.0				7.0	
Init.Turb	5.9	6.1	5.2	5.7	5.8	6.1
Removal						
5 min	5.3	1.8	1.3	1.1	1.2	1.0
20 min	4.9	0.5	0.5	0.4	0.4	0.3
removal/%	16.9	91.8	90.4	93.0	93.1	95.1
pH				6.70		6.67

Remarks
Jar test indicates that anywhere from 12-14 mg/l of $FeCl_3$ will yield very good results.
Rapid mix for two minutes
Tapered flocculation of :
5 min at 60 RPM
5 min at 30 RPM
5 min at 15 RPM

COAGULATION RUN #17 04/11/91

FEED WATER CHARACTERISTICS:

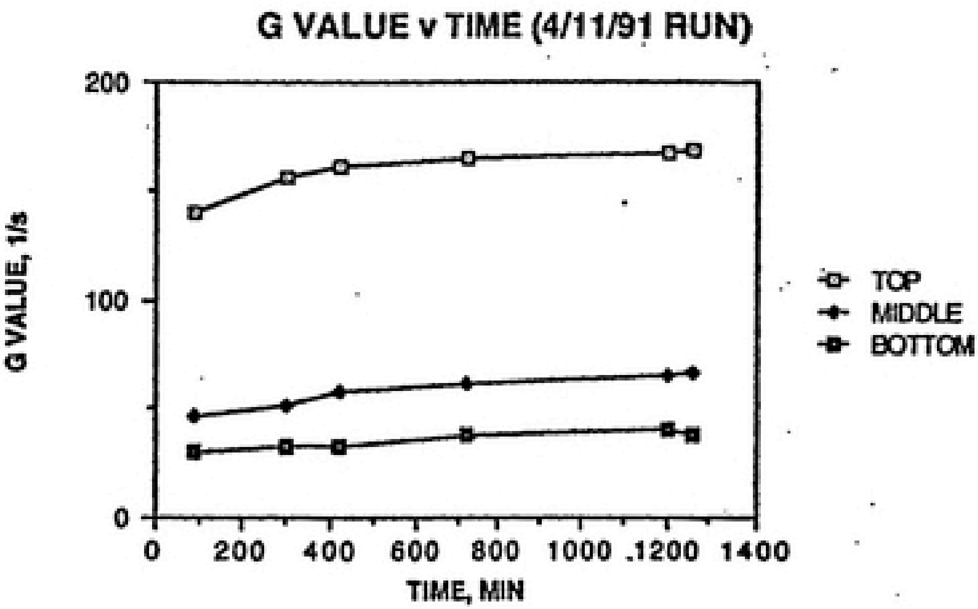
Turbidity:	5 NTU
Coagular: FeCl	12 mg/l
Polymer:	0 mg/l
Alkalinity: NaHCO3	42 mg/l
Temperature:	20 C
Flowrate	13 GPM

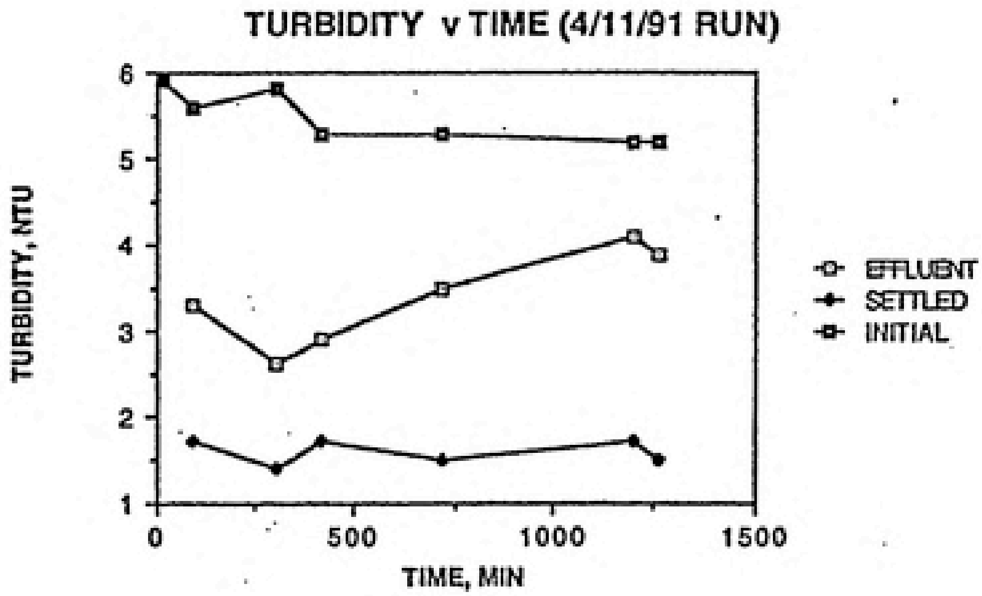
Media:	3/8 " 3M	B.-Height	1.33 '	Downflow
	1/2 " 3M	B.-Height	1.67 '	Downflow
	3/4" 3M	B.-Height	1.58 '	Downflow

SAMPLE #	TIME min	HEADLOSS: TOP mm	MID PT mm	O'ALL mm	G-VALUE: TOP 1/s	MID PT 1/s	BOTTOM 1/s	3M MEDIA: TURBIDITY,NTU EFFLUENT	SETTLED	FEED SETTLED	INT TURB
0	15			153						0.4	5.9
1	90	155	187	202	140.1	46.0	30.4	3.3	1.7	0.3	5.6
2	300	195	235	252	157.1	51.4	32.4	2.6	1.4	0.4	5.8
3	420	205	255	272	161.1	57.5	32.4	2.9	1.7	0.4	5.3
4	720	215	270	292	165.0	60.3	36.8	3.5	1.5	0.3	5.3
5	1200	222	286	311	167.7	65.0	39.2	4.1	1.7	0.4	5.2
6	1260	226	291	314	169.2	65.5	37.6	3.9	1.5	0.4	5.2

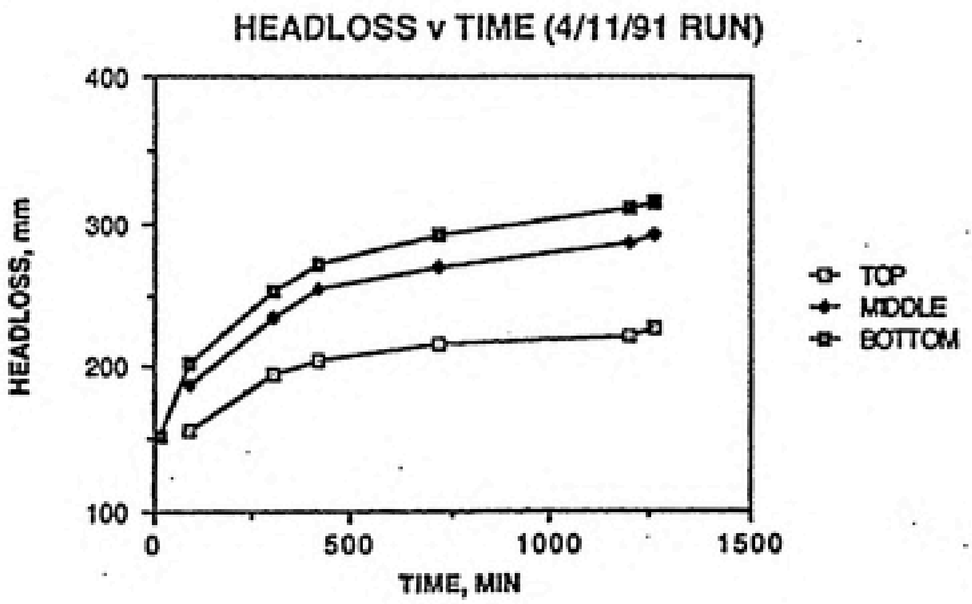
Remarks:

1. The samples for this run were taken using the large tubing to fill jartest jar from bottom.
2. Run was terminated after water tanks ran dry; the bed drained partially.


G VALUE v TIME (4/11/91 RUN)
G VALUE, 1/s
200
100
0
0
200
400
600
800
1000
1200
1400
TIME, MIN
TOP
MIDDLE
BOTTOM



TURBIDITY v TIME (4/11/91 RUN)
TURBIDITY, NTU
6
5
4
3
2
1
0
500
1000
1500
TIME, MIN
EFFLUENT
SETTLED
INITIAL



HEADLOSS v TIME (4/11/91 RUN)
HEADLOSS, mm
400
300
200
100
0
500
1000
1500
TIME, MIN
TOP
MIDDLE
BOTTOM

Jartest Date: 04/17/91

Jar test for coagulation run #18 (100 NTU)

Water:	Water from outside tanks	
Temp.:	19.0	
Coagulant:	FeCl3	
Turbidity:	100 NTU	as Kaolinite
Alkalinity: NaHCO3	42 mg/l	additional

Jar	2	3	4	5	6
Parameter					
FeCl3,mg/l	15	16	18	20	22
Poly/mg/l	0.0	0.0	0.0	0.0	0.0
Init. pH	7.3				7.3
Init.Turb	100.0	100.0	103.0	101.0	97.0
Removal					
5 min	0.7	2.0	1.4	1.0	10.0
20 min	0.3	0.3	0.4	0.4	1.4
removal/%	99.7	99.7	99.6	99.6	0.3
pH	6.60		6.55		6.50

Remarks

Based on this and the previous jar test, the optimal dosage of FeCl3 appears to be in the range of 16-20 mg/l.

Rapid mix for two minutes

Tapered flocculation of :

5 min at 60 RPM

5 min at 30 RPM

5 min at 15 RPM

COAGULATION RUN #18 04/17/91

FEED WATER CHARACTERISTICS:

Turbidity:	100 NTU
Coagular: FeCl	18 mg/l
Polymer:	0 mg/l
Alkalinity: NaHCO3	42 mg/l
Temperature:	19 C
Flowrate	13 GPM

Media:	3/8 " 3M	B.-Height	1.33 '	Downflow
	1/2 " 3M	B.-Height	1.67 '	Downflow
	3/4" 3M	B.-Height	1.58 '	Downflow

		HEADLOSS:			G-VALUE:			3M MEDIA:			
SAMPLE	TIME	TOP	MID PT	O'ALL	TOP	MID PT	BOTTOM	TURBIDITY,NTU		FEED	INT
#	min	mm	mm	mm	1/s	1/s	1/s	EFFLUENT	SETTLED	SETTLED	TURB
0	0	175	226	245	148.9	58.0	34.2	32.0	9.7	0.7	96.0
1	60			318				35.0	10.3		
2	105			280				160.0	7.3	0.7	91.0
3	165			312							

Remarks:

1. The samples for this run were taken using the large tubing to fill jartest jar from bottom.
2. The bed was partially cleaned after sample no. 2 due to demonstrate the cleaning method and efficiency.

COAGULATION RUN #19 04/19/91

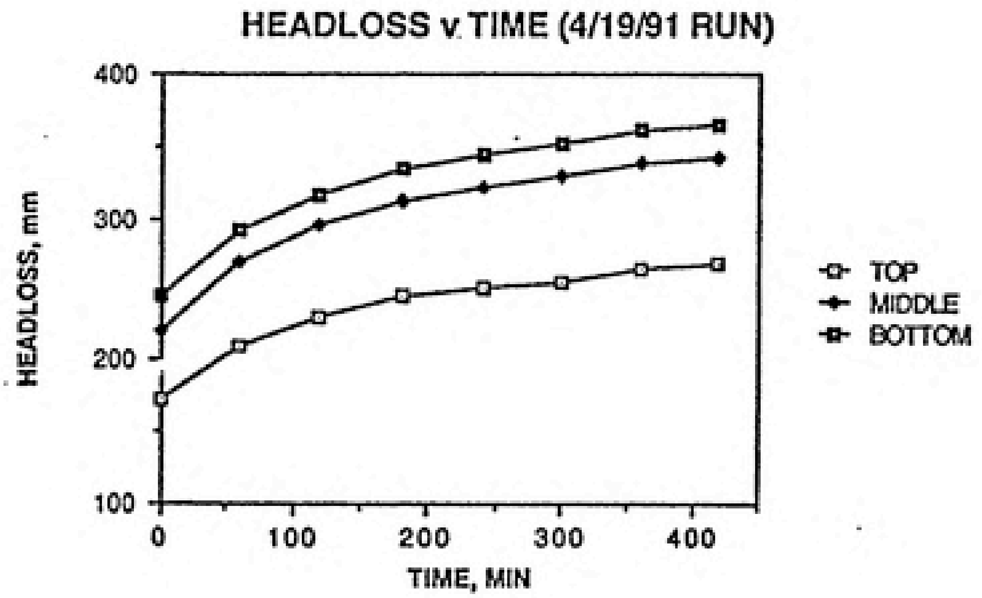
FEED WATER CHARACTERISTICS:

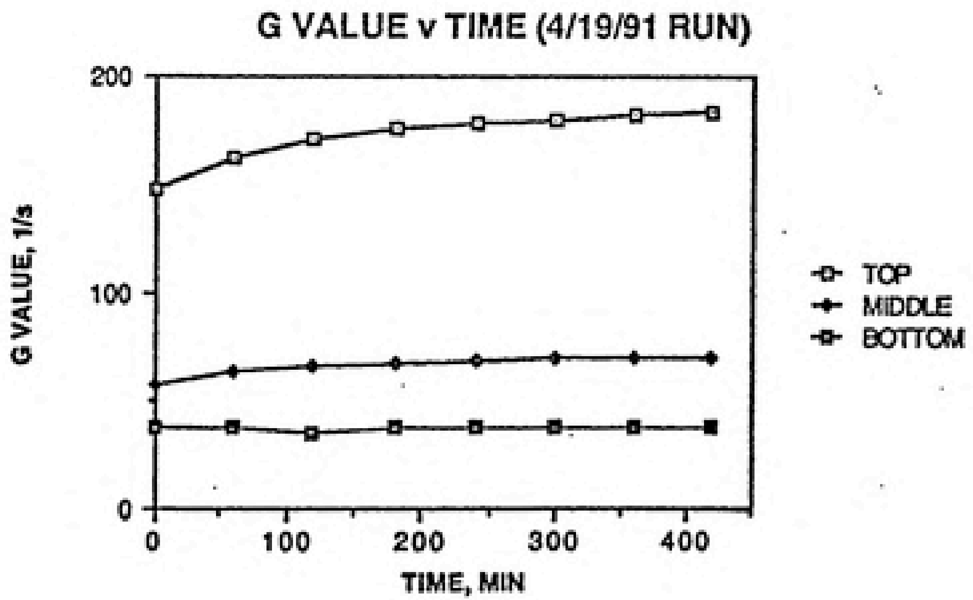
Turbidity:	100 NTU
Coagulai : FeCl	18 mg/l
Polymer: .	0 mg/l
Alkalinity: NaHCO3	42 mg/l
Temperature:	19 C
Flowrate	13 GPM

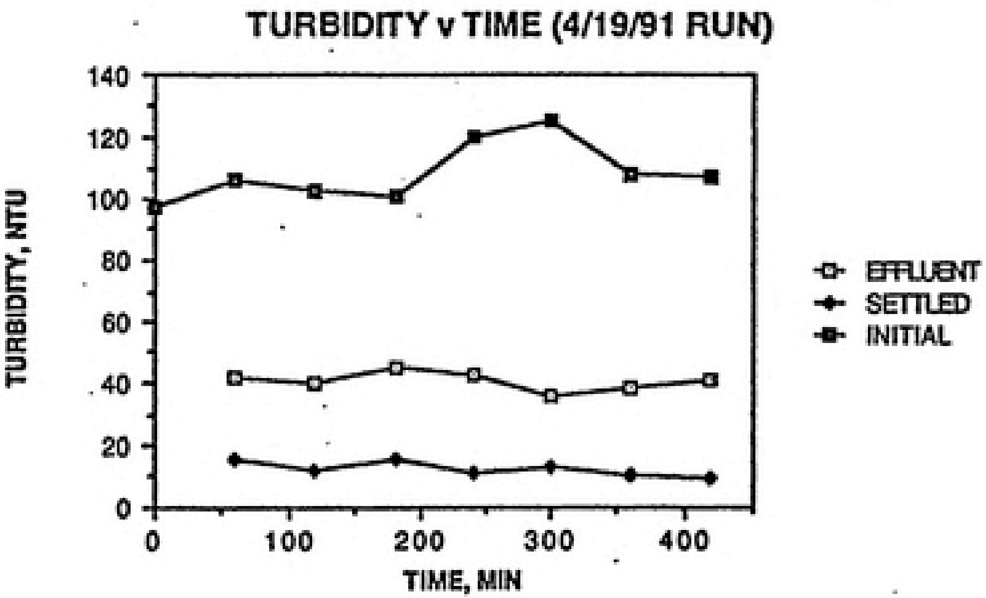
Media:	3/8 " 3M	B.-Height	1.33 '	Downflow
	1/2 " 3M	B.-Height	1.67 '	Downflow
	3/4" 3M	B.-Height	1.58 '	Downflow

		HEADLOSS:			G-VALUE:			3M MEDIA:			
SAMPLE	TIME	TOP	MID PT	O'ALL	TOP	MID PT	BOTTOM	TURBIDITY,NTU		FEED	INT
#	min	mm	mm	mm	1/s	1/s	1/s	EFFLUENT	SETTLED	SETTLED	TURB
0	0	172	222	245	147.6	57.5	37.6			0.8	97.0
1	60	210	270	292	163.1	62.9	36.8	42.0	16.0	1.2	106.0
2	120	231	296	316	171.0	65.5	35.1	40.0	12.3	1.4	103.0
3	180	245	313	335	176.1	67.0	36.8	45.0	15.8	0.9	101.0
4	240	251	322	345	178.3	68.5	37.6	43.0	11.5	1.0	120.0
5	300	255	329	352	179.7	69.9	37.6	36.0	12.7	1.0	125.0
6	360	264	338	361	182.8	69.9	37.6	38.0	10.5	0.8	108.0
7	420	268	342	365	184.2	69.9	37.6	41.0	9.8	1.0	107.0

Remarks:


HEADLOSS v TIME (4/19/91 RUN)
HEADLOSS, mm
400
300
200
100
0
100
200
300
400
TIME, MIN
TOP
MIDDLE
BOTTOM


G VALUE v TIME (4/19/91 RUN)
G VALUE, 1/s
200
100
0
0
100
200
300
400
TIME, MIN
TOP
MIDDLE
BOTTOM



TURBIDITY v TIME (4/19/91 RUN)
TURBIDITY, NTU
TIME, MIN
140
120
100
80
60
40
20
0
0
100
200
300
400
EFFLUENT
SETTLED
INITIAL

COAGULATION RUN #20 04/23/91

FEED WATER CHARACTERISTICS:

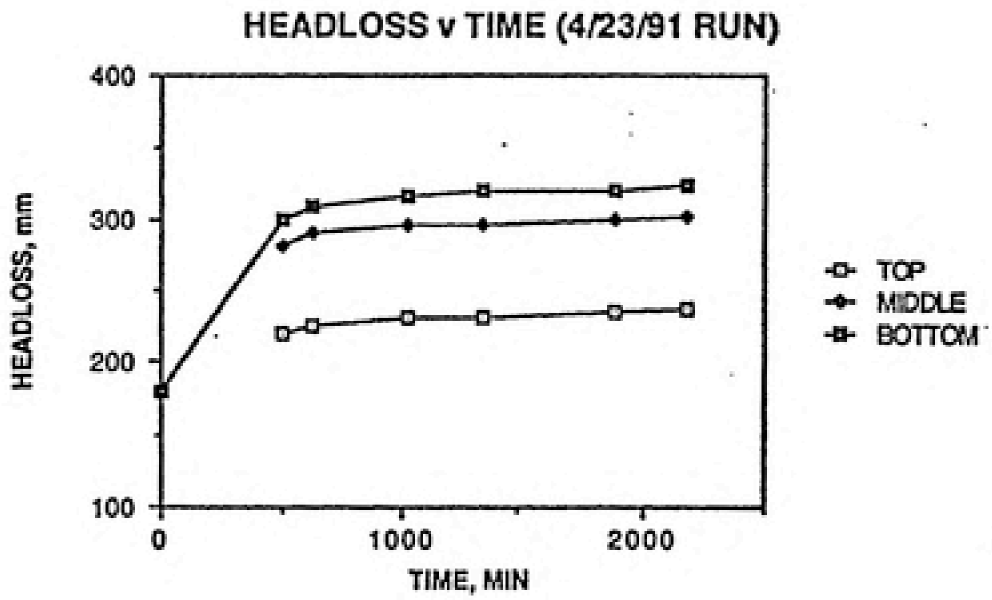
Turbidity:	20 NTU
Coagular: FeCl	14 mg/l
Polymer:	0 mg/l
Alkalinity: NaHCO3	42 mg/l
Temperature:	19 C
Flowrate	8 GPM

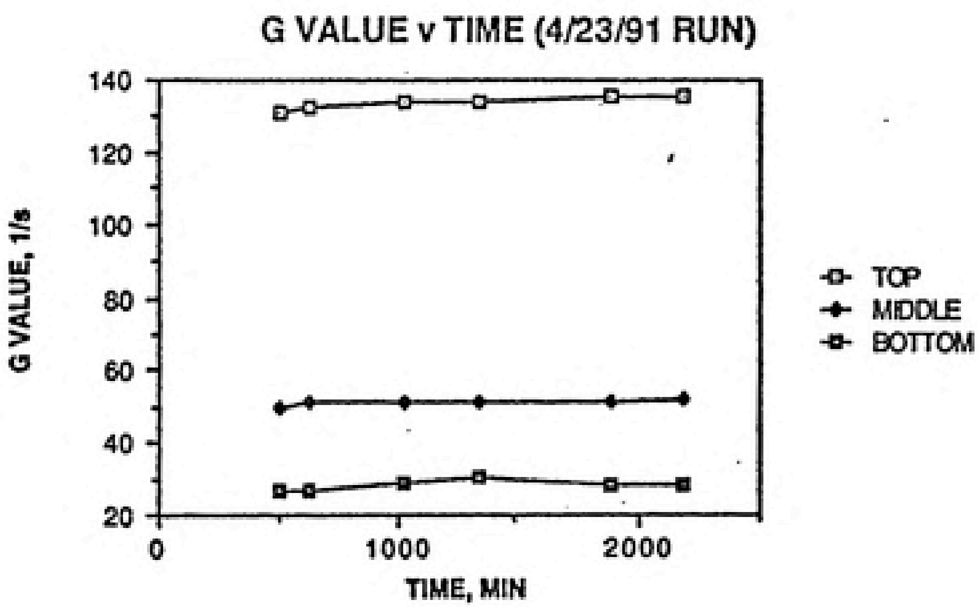
Media:	3/8 " 3M	B.-Height	1.33 '	Downflow
	1/2 " 3M	B.-Height	1.67 '	Downflow
	3/4" 3M	B.-Height	1.58 '	Downflow
	3/4" NORPAK	B.-Height (O'flow column)	4.50 '	Upflow

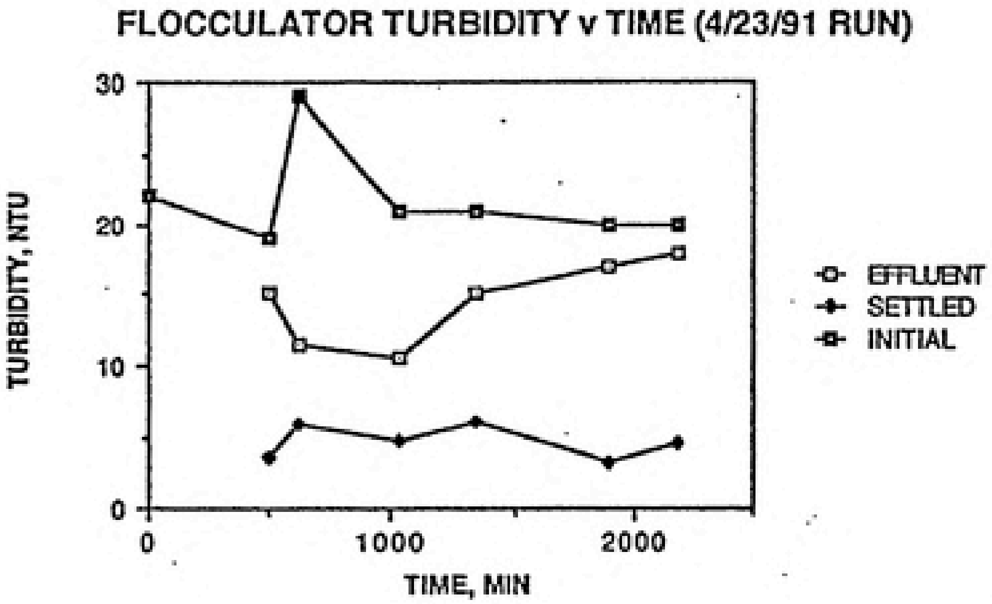
		HEADLOSS:			G-VALUE:			3M MEDIA:		OVERFLOW:			
SAMPLE	TIME	TOP	MID PT	O'ALL	TOP	MID PT	BOTTOM	TURBIDITY,NTU		TURBIDITY,NTU		FEED	INT
#	min	mm	mm	mm	1/s	1/s	1/s	EFFLUENT	SETTLED	EFFLUENT	SETTLED	SETTLED	TURB
0	0			181								0.4	22.0
1	505	220	281	300	130.9	49.8	26.8	15.0	3.5	65.0	3.2	0.2	19.0
2	625	225	290	309	132.4	51.4	26.8	11.5	5.8	15.0	4.2	1.3	29.0
3	1030	230	295	317	133.9	51.4	28.9	10.5	4.8	15.0	4.4	1.1	21.0
4	1345	231	295	320	134.2	51.0	30.8	15.0	6.0	3.0	1.4	0.3	21.0
5	1885	235	299	320	135.3	51.0	28.2	17.0	3.3	1.8	1.0	0.5	20.0
6	2185	236	302	323	135.6	51.8	28.2	18.0	4.5	5.6	1.0	0.5	20.0

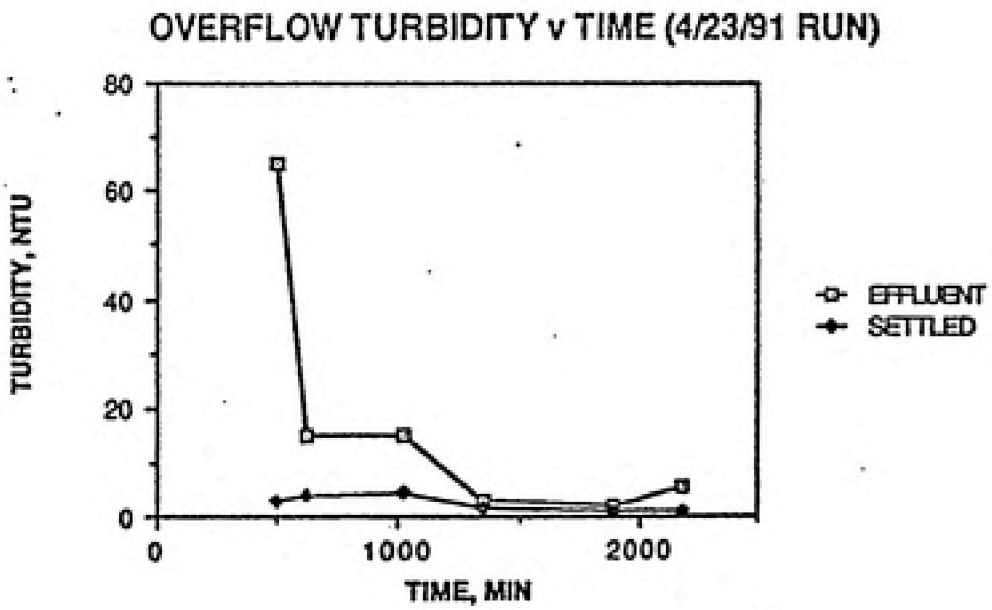
Remarks:

1. After sample no. 3 the loading in the overflow column was lowered from 16.0 GPM/Ft^2 to 2.6 GPM/Ft^2 to match the loading rate at the bottom of the flocculator.
2. After sample no. 5, the loading rate to the overflow column was increased to 5.0 GPM/Ft^2


HEADLOSS v TIME (4/23/91 RUN)
HEADLOSS, mm
400
300
200
100
0
1000
2000
TIME, MIN
TOP
MIDDLE
BOTTOM


G VALUE v TIME (4/23/91 RUN)
G VALUE, 1/s
140
120
100
80
60
40
20
0
1000
2000
TIME, MIN
TOP
MIDDLE
BOTTOM


FLOCCULATOR TURBIDITY v TIME (4/23/91 RUN)
TURBIDITY, NTU
0
10
20
30
0
1000
2000
TIME, MIN
EFFLUENT
SETTLED
INITIAL


OVERFLOW TURBIDITY v TIME (4/23/91 RUN)
TURBIDITY, NTU
0
20
40
60
80
0
1000
2000
TIME, MIN
EFFLUENT
SETTLED

COAGULATION RUN #21 04/29/91

FEED WATER CHARACTERISTICS:

Turbidity:	20 NTU
Coagulai : FeCl	14 mg/l
Polymer:	0 mg/l
Alkalinity: NaHCO3	42 mg/l
Temperature:	20 C
Flowrate	6 GPM

Media:			
3/8 " 3M	B.-Height	1.33 '	Downflow
1/2 " 3M	B.-Height	1.67 '	Downflow
3/4" 3M	B.-Height	1.58 '	Downflow
3/4" NORPAK	B.-Height (O'flow column)	4.50 '	Upflow

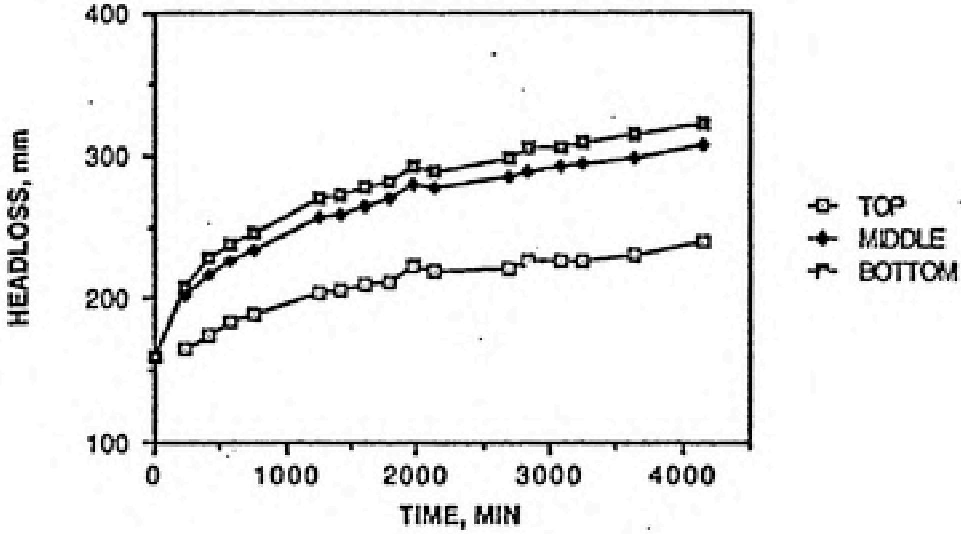
		HEADLOSS:			G-VALUE:			3M MEDIA: TURBIDITY,NTU		OVERFLOW TURBIDITY,NTU		FEED	INT
SAMPLE #	TIME min	TOP mm	MID PT mm	O'ALL mm	TOP 1/s	MID PT 1/s	BOTTOM 1/s	EFFLUENT	SETTLED	EFFLUENT	SETTLED	SETTLED	TURB
0	0			160									
1	30												18.0
2	225	165	203	208	98.2	34.0	11.9	6.0	3.6	1.8		0.6	18.0
3	405	175	218	228	101.1	36.2	16.9	16.0	4.9	1.7		0.6	17.0
4	585	184	226	237	103.7	35.6	17.7	13.5	4.5	1.4		0.5	19.0
5	765	190	235	246	105.4	37.0	17.7	11.0	4.7	1.5		0.7	23.0
6	1245	205	256	270	109.5	39.4	20.0	10.5	3.5	1.3		0.5	18.0
7	1425	207	258	271	110.0	39.4	19.2	16.0	4.5	1.2		0.5	20.0
8	1605	210	264	277	110.8	40.6	19.2	20.0	3.9	1.2		0.6	18.0
9	1785	211	269	281	111.0	42.0	18.5	20.0	4.1	1.7		0.6	17.0
10	1965	223	278	291	114.2	40.9	19.2	24.0	4.5	1.7		0.7	20.0
11	2145	220	277	288	113.4	41.7	17.7	18.0	5.3	1.6		0.5	18.0
12	2685	222	285	297	113.9	43.8	18.5		4.8	2.5		0.3	18.0
13	2835	226	288	305	114.9	43.5	22.0	11.0	3.2	2.3		0.6	19.0
14	3075	227	291	305	115.2	44.2	20.0	11.0	4.4	1.5	0.9	0.5	21.0
15	3255	227	293	308	115.2	44.8	20.7	16.0	3.3	1.7	1.1	0.6	17.0
16	3645	230	298	314	115.9	45.5	21.3	11.0	3.1	1.7	1.1	0.6	23.0
17	4155	239	306	321	118.2	45.2	20.7	17.0	5.0	2.3	1.3	0.4	18.0

Remarks:

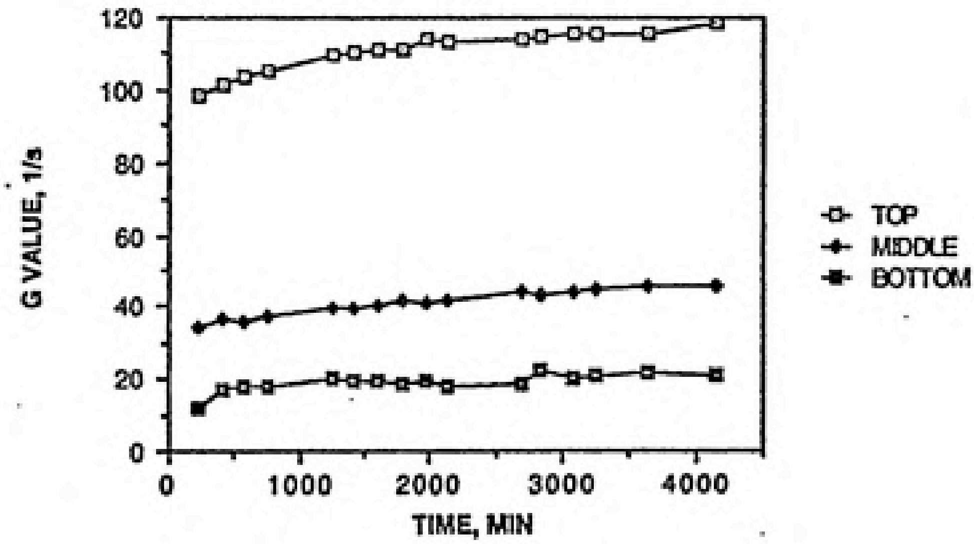
1. Loading rate to the overflow column was 3.0 GPM/Ft^2 through the entire run.
2. After sample no. 15, lowered headloss through bottom tubing to clear tubing path.
3. Overflow column sample nos. 2-13 were taken from the discharge tubing.
   Sample nos. 14-17 were taken from the top of the column and settled.
   Samples from the discharge tubing were:

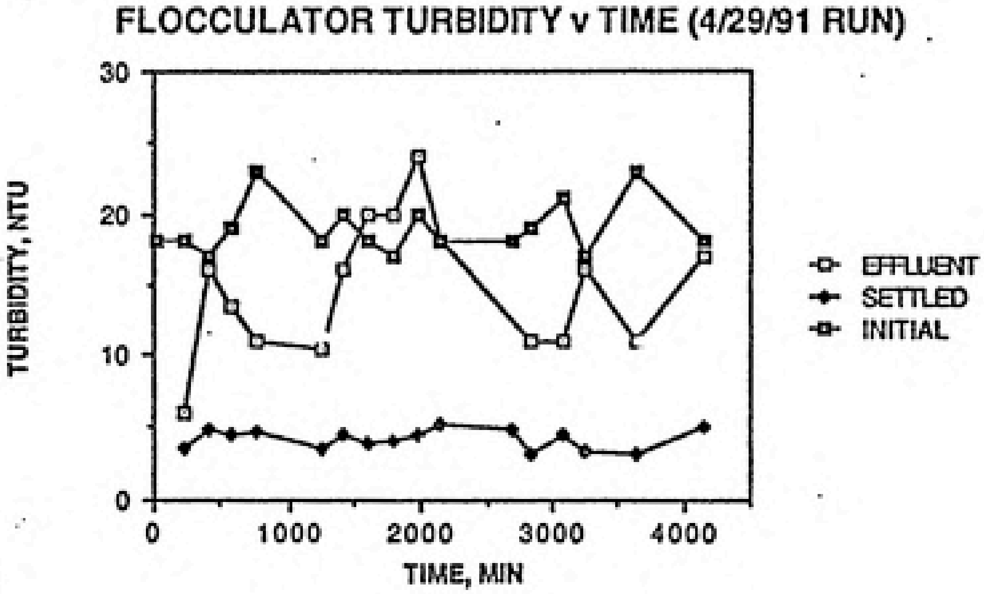
14	2.8
15	2.9
16	3.4
17	3.3

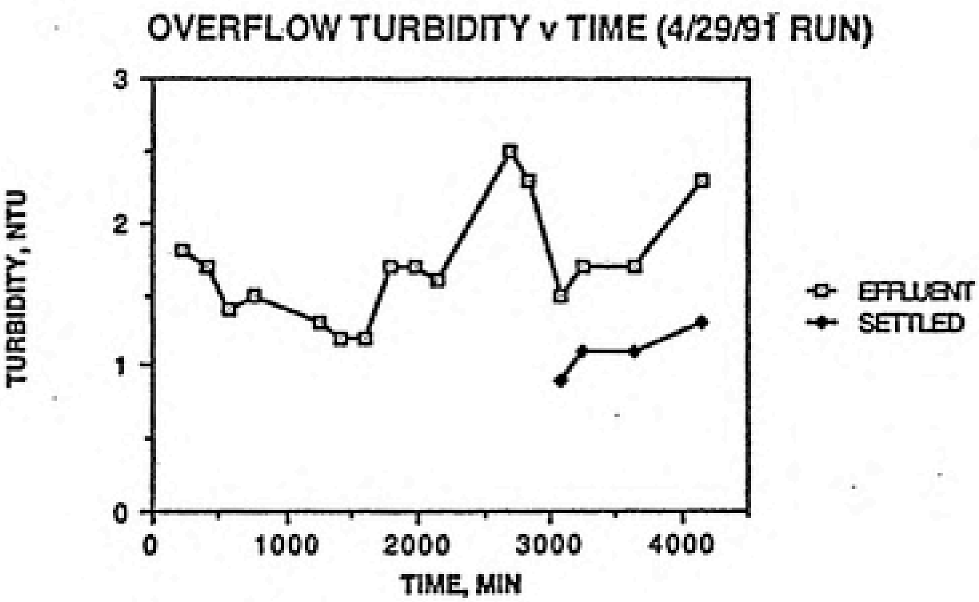
HEADLOSS v TIME (4/29/91 RUN)



G VALUE v TIME (4/29/91 RUN)




FLOCCULATOR TURBIDITY v TIME (4/29/91 RUN)
TURBIDITY, NTU
TIME, MIN
0
10
20
30
0
1000
2000
3000
4000
EFFLUENT
SETTLED
INITIAL


OVERFLOW TURBIDITY v TIME (4/29/91 RUN)
TURBIDITY, NTU
TIME, MIN
0
1
2
3
0
1000
2000
3000
4000
EFFLUENT
SETTLED

COAGULATION RUN #22 05/08/91

FEED WATER CHARACTERISTICS:

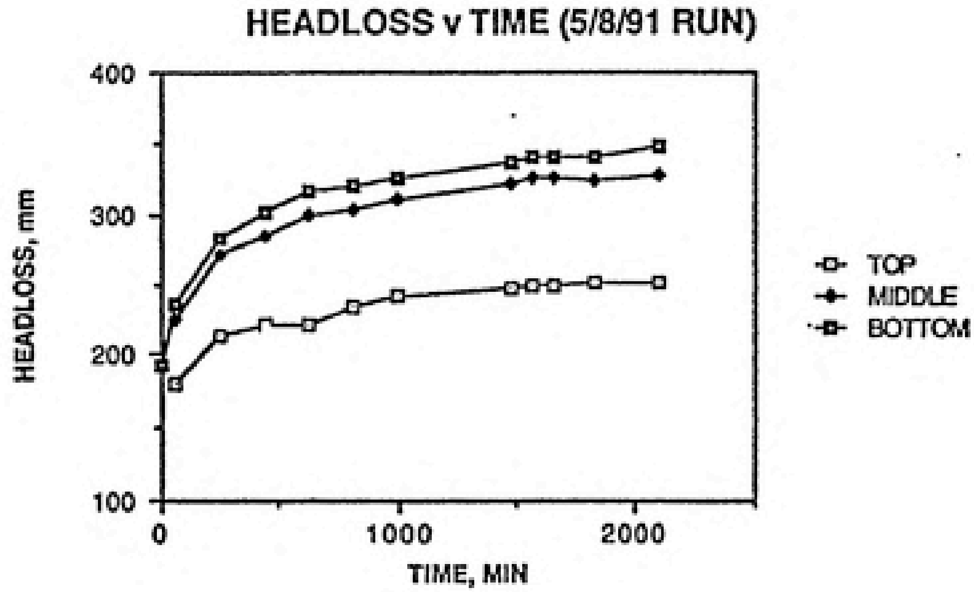
Turbidity:	20 NTU
Coagular: FeCl	14 mg/l
Polymer:	0 mg/l
Alkalinity: NaHCO3	42 mg/l
Temperature:	20.5-22.0 C
Flowrate	6 GPM

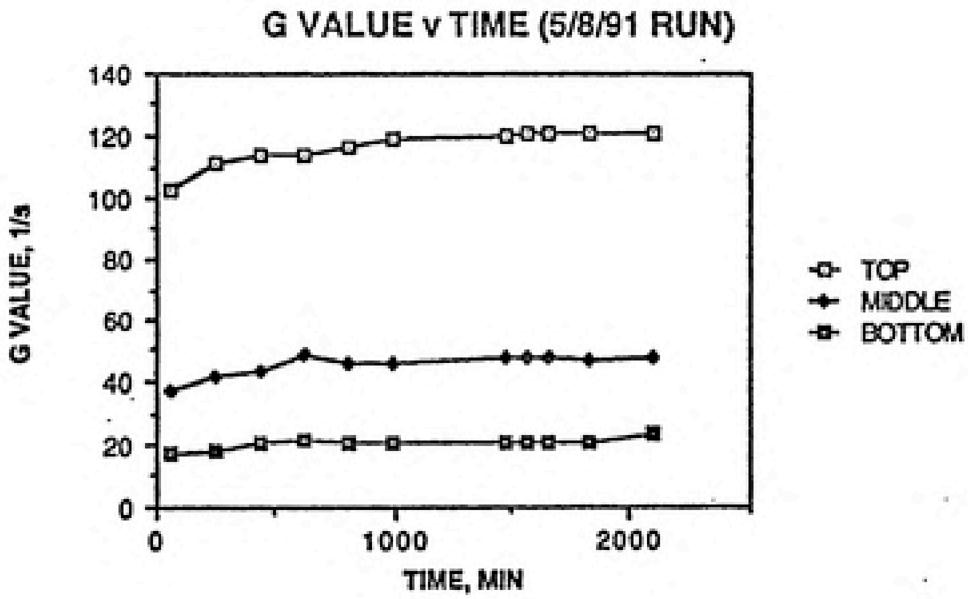
Media:				
3/8 " 3M	B.-Height		1.33 '	Downflow
1/2 " 3M	B.-Height		1.67 '	Downflow
3/4" 3M	B.-Height		1.58 '	Downflow
3/4" NORPAK	B.-Height	(O'flow column)	4.50 '	Upflow

SAMPLE #	TIME min	TOP mm	HEADLOSS: MID PT mm	O'ALL mm	G-VALUE: TOP 1/s	MID PT 1/s	BOTTOM 1/s	3M MEDIA: TURBIDITY,NTU EFFLUENT	SETTLED	OVERFLOW: TURBIDITY,NTU EFFLUENT	SETTLED	FEED SETTLED	INT TURB
0	0			194						2.5		0.6	13.0
1	60	180	225	236	102.6	37.0	17.7	10.1	4.2	2.6	2.3	0.5	21.0
2	255	213	271	283	111.6	42.0	18.5	10.5	3.3	2.5	1.9	0.6	24.0
3	450	222	285	301	113.9	43.8	21.3	14.0	6.6	2.1	1.3	0.5	25.0
4	630	222	299	316	113.9	48.4	22.0	10.0	4.7	1.9	1.4	0.4	24.0
5	810	234	304	320	116.9	46.2	21.3	9.5	4.2	1.8	1.4	0.7	20.0
6	990	241	311	326	118.7	46.2	20.7	10.7	4.7	2.0	1.8	0.7	20.0
7	1470	247	321	336	120.1	47.5	20.7	16.0	4.9	2.0	1.2	0.8	26.0
8	1560	249	325	340	120.6	48.1	20.7	21.0	4.7	2.1	1.2	0.7	20.0
9	1650	250	325	341	120.9	47.8	21.3	29.0	5.5	1.9	1.1	0.7	21.0
10	1830	251	324	340	121.1	47.2	21.3	38.0	3.5	3.7	1.3	0.7	21.0
11	2100	251	327	347	121.1	48.1	23.8	18.0	4.5	3.6	1.1	0.6	23.0

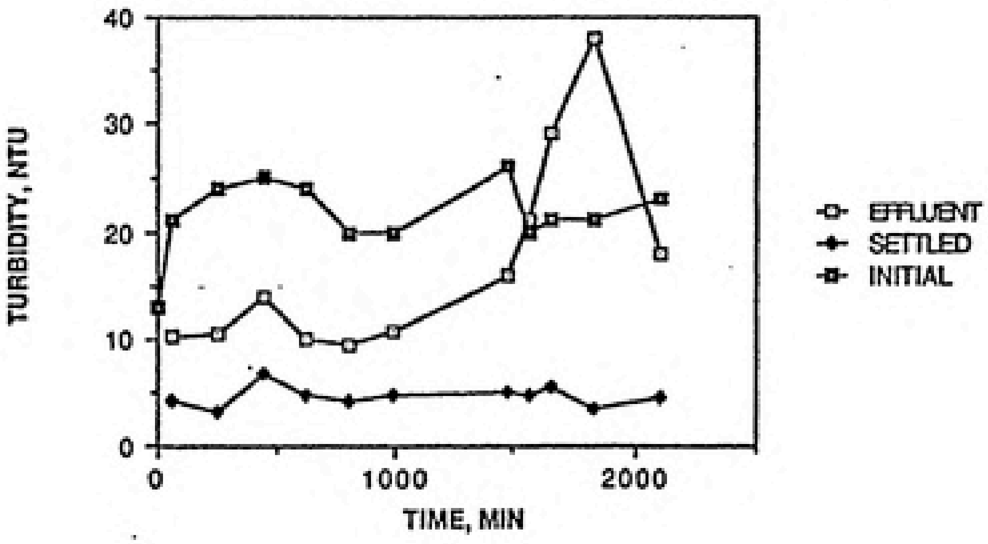
Remarks:

1. Loading rate to the overflow column was 5.0 GPM/Ft^2 through the entire run.
2. Overflow column samples were taken from the discharge tubing.
3. By sample no. 10 (30.5 hours) the Norpak was full of flocs and many flocs were suspended above the bed.

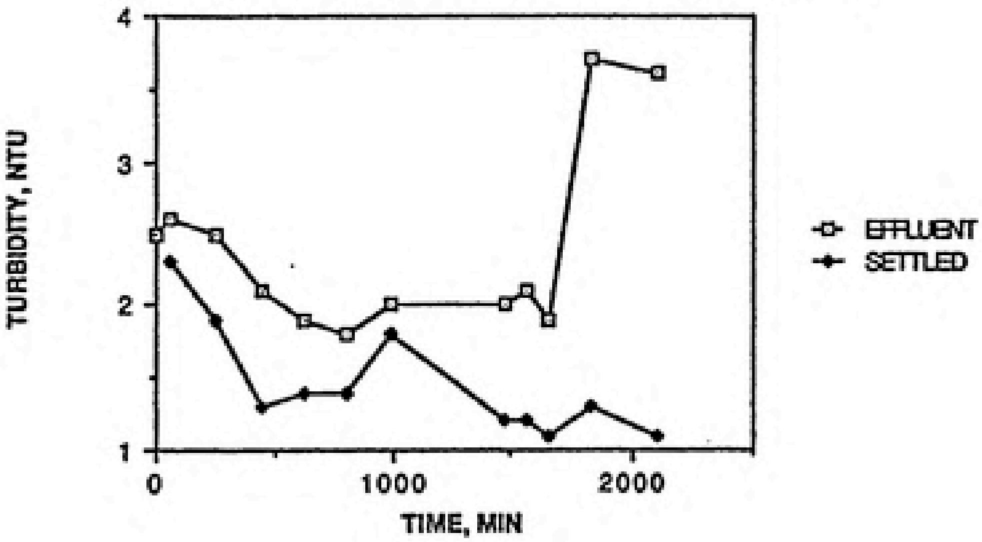

HEADLOSS v TIME (5/8/91 RUN)
HEADLOSS, mm
400
300
200
100
0
1000
2000
TIME, MIN
TOP
MIDDLE
BOTTOM


G VALUE v TIME (5/8/91 RUN)
G VALUE, 1/s
140
120
100
80
60
40
20
0
1000
2000
TIME, MIN
TOP
MIDDLE
BOTTOM

FLOCCULATOR TURBIDITY v TIME (5/8/91 RUN)



OVERFLOW TURBIDITY v TIME (5/8/91 RUN)



Monthly Progress Report / Buoyant Coarse Media Flocculator

May 15 to June 30, 1991

This report covers one and one-half months of pilot plant work in both Baity Lab and at OWASA's Jones Ferry Road Water Treatment Plant. Six flocculation runs were made with the tapered bed filled with ceramic media or ceramic media over Norpak.. For five of these runs, the overflow column was filled with Norpak media. Ferric chloride was used as the coagulant for the two runs conducted in Baity Lab. The four runs conducted at OWASA used water from the rapid mix basin to which alum, polymer, PAC, and potassium permanganate had been added. Water temperatures ranged from 23.5 to 27.0°C The results are presented below as bullets.

- Of the two runs conducted at Baity Lab, the first run was with two layers of ceramic media over a layer of 1" Norpak, all in the downflow configuration. Flow rate was 6 GPM. $FeCl_3$ concentration was 14 mg/l. Effluent turbidities averaged 5.0 NTU, settling to 3.5 NTU after the bed had ripened. The run was terminated after the Norpak media separated from the rest of the bed after 92.5 hours of run time. Before the Norpak separated, settleable floc was exiting the bed. The second run was conducted with three ceramic layers in the flocculator, followed by Norpak in an upflow mode in the overflow column. Flow rate to the flocculator was 6 GPM for most of the run. Twelve mg/l of $FeCl_3$ was used. There were not sufficient data points in this run to draw any significant conclusions. The run was made to demonstrate flocculator operation to CDM and EIMCO during the technical review meeting. Runs 20-22 were conducted in this configuration and are documented in the April report.

- The next four runs were made at the OWASA Treatment Plant using water from the rapid mix basin to which OWASA had already added chemicals. Chemical dosages were 35 mg/l alum, 0.1 mg/l polymer, 4.5 mg/l PAC, and 0.5 mg/l $KMNO_4$. All runs were made with ceramic media in the flocculator and Norpak in the overflow column. During the first run three layers of ceramic were in the flocculator, flow rate was 6 GPM, and the loading rate to the overflow column was 4.1 GPM/ft^2. Headloss built rapidly throughout the run, finally reaching 630 mm after the level of the overflow column was lowered by 1 foot. The bed was partially cleaned twice by increasing the flow rate. Only after 27 hours of operation did settleable floc exit the bed. At that point, turbidity was 2.1 NTU, settling to 0.5 NTU. No substantial amount of floc left the overflow column. During this run, the water from OWASA's sedimentation basin was 0.1 NTU, from the pulsator was 0.3 NTU, and from the flocculator was 4.5 NTU, settling to 0.4 NTU after 20 minutes. These operating conditions at OWASA were fairly constant during all four runs.

- The next run was conducted with the same media configuration as above, but with a flow rate of 12 GPM and a loading rate to the overflow column of 3 GPM/ft^2. The intention of this run was to see if floc could be forced deeper into the bed by the higher flow rate. Headloss built too rapidly to allow any meaningful turbidity data to be acquired. After 50 minutes of run time, overall headloss had increased from 426 mm to 670 mm.

- The final two runs were made with a shortened media bed. The top layer of 3/8" media was removed since most of the headloss buildup occurred in this media. The first of these runs was conducted at 12 GPM and a 3GPM/ft^2 loading rate. When the bed had ripened after 18 hours of run time, the effluent turbidity was 3.4 NTU, settling to 0.8 NTU. However, the top of the bed dropped below the bottom of the screen and a separation opened at approximately 37 cm below the screen. It was not possible to close the separation, even by raising the level of the overflow column. The second run made with the shorter media bed was conducted at 6 GPM and a 3 GPM/ft^2 loading rate. After running for 14.5 hours, the effluent turbidity was 5.0 NTU, settling to 1.1 NTU.

Plans for July/August:

Additional flocculation runs will be made at the OWASA plant to test other combinations of media and flow rate. Cleaning characteristics of the bed will be tested using both increased water flow rates and air scouring. It is expected that the run time of a bed can be extended substantially by cleaning the media and lowering the headloss.

COAGULATION RUN #23 05/20/91

FEED WATER CHARACTERISTICS:

Turbidity:	20 NTU
Coagular: FeCl	14 mg/l
Polymer:	0 mg/l
Alkalinity: NaHCO3	42 mg/l
Temperature:	23.5 C
Flowrate	6 GPM

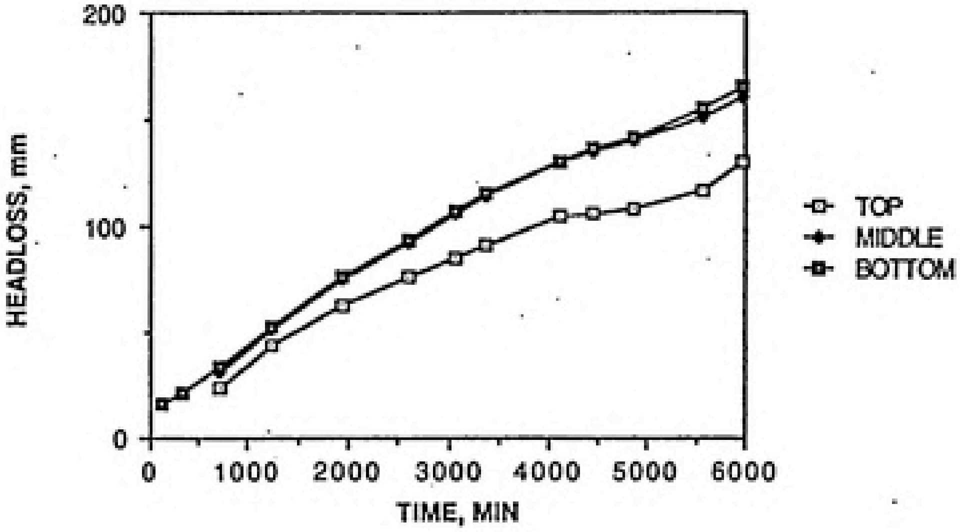
Media:	3/8 " 3M	B.-Height	1.33 '	Downflow
	1/2 " 3M	B.-Height	1.67 '	Downflow
	1" Norpak	B.-Height	1.58 '	Downflow

		HEADLOSS:			G-VALUE:			FLOCCULATOR			
SAMPLE	TIME	TOP	MID PT	O'ALL	TOP	MID PT	BOTTOM	TURBIDITY,NTU		FEED	INT
#	min	mm	mm	mm	1/s	1/s	1/s	EFFLUENT	SETTLED	SETTLED	TURB
0	120			16						0.5	15.0
1	320			21				14.0	10.0	0.4	20.0
2	705	23	31	33	61.1	26.0	8.4	6.0	5.6	0.5	18.0
3	1240	44	51	52	84.5	24.3	6.0	5.6	5.1	0.6	20.0
4	1950	62	75	76	100.3	33.2	6.0	4.2	3.5	0.5	19.0
5	2595	76	92	93	111.1	36.8	6.0	3.1	2.9	0.3	19.0
6	3060	84	106	107	116.8	43.2	6.0	3.5	2.9	0.5	17.5
7	3360	91	114	115	121.5	44.1	6.0	4.3	3.5	0.6	17.5
8	4110	104	130	131	129.9	46.9	6.0	5.9	5.3	1.5	21.0
9	4425	106	136	137	131.2	50.4	6.0	4.9	3.8	0.7	19.0
10	4845	108	140	141	132.4	52.0	6.0	7.5	3.9	0.8	20.0
11	5550	117	152	155	137.8	54.4	10.3	5.2	3.9	0.8	22.0
12	5970	130	160	165	145.3	50.4	13.3	5.7	3.8	0.8	18.0

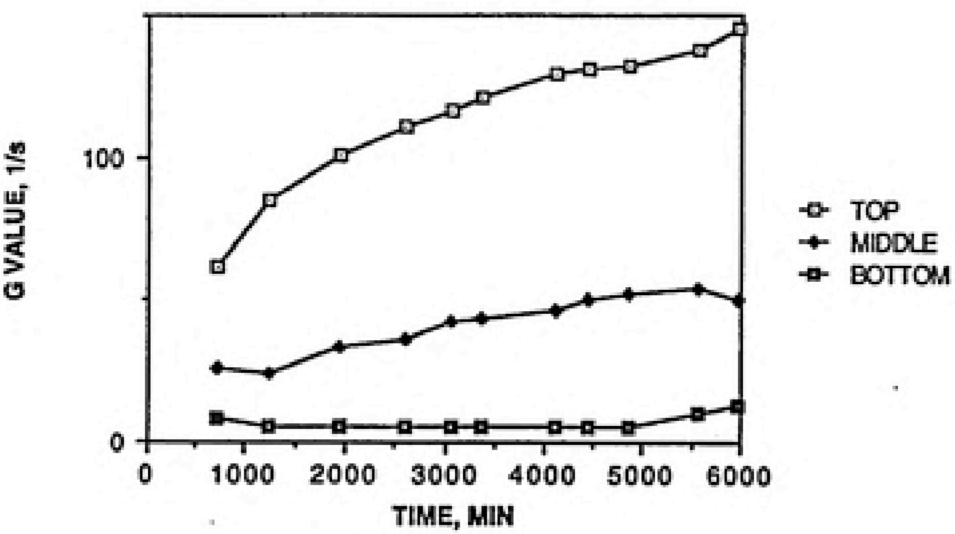
Remarks:

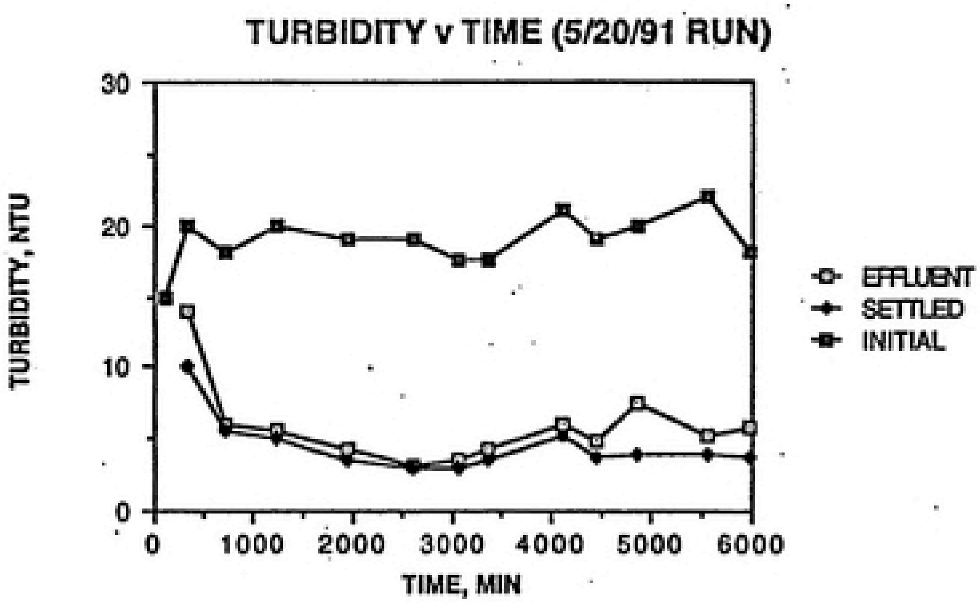
1. This flocculation run was to test Norpak media in the downflow configuration as the bottom media in the flocculator.
2. By sample no. 4, very few floc had left the Norpak media at the bottom of the flocculator.
3. By sample no. 6, a large volume of floc were leaving the Norpak media.
4. Between sample nos. 11 and 12, the Norpak layer separated from the upper media
5. Results indicate that by sample no. 10 at 80.75 hours, settlable floc was exiting the flocculator.

HEADLOSS v TIME (5/20/91 RUN)



G VALUE v TIME (5/20/91 RUN)




TURBIDITY v TIME (5/20/91 RUN)
TURBIDITY, NTU
TIME, MIN
0
10
20
30
1000
2000
3000
4000
5000
6000
EFFLUENT
SETTLED
INITIAL

COAGULATION RUN #24 5/31/91

FEED WATER CHARACTERISTICS:

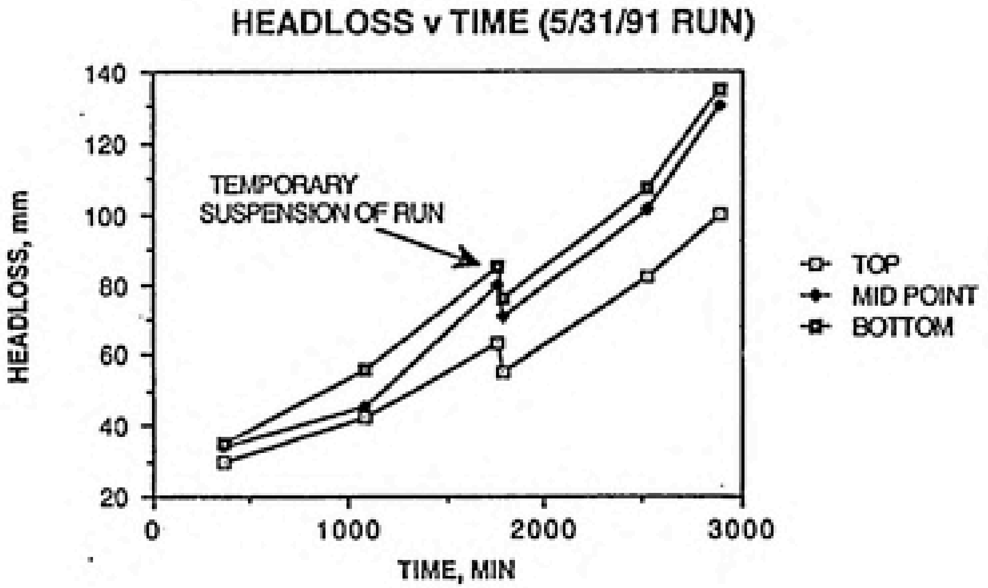
Turbidity:	20 NTU
Coagulai: FeCl	12 mg/l
Polymer:	0 mg/l
Alkalinity: NaHCO3	42 mg/l
Temperature:	26 C
Flowrate	6 GPM

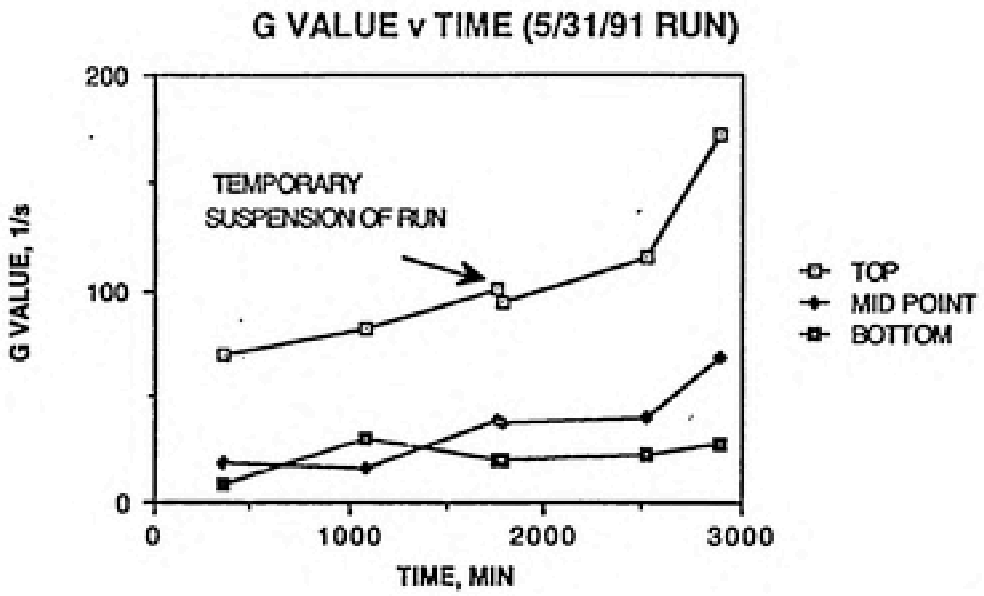
Media:	3/8 " 3M	B.-Height	1.33 '	Downflow
	1/2 " 3M	B.-Height	1.67 '	Downflow
	3/4 " 3M	B.-Height	1.58 '	Downflow
	1" Norpak	B.-Height (O'flow column)	4.5 '	Upflow

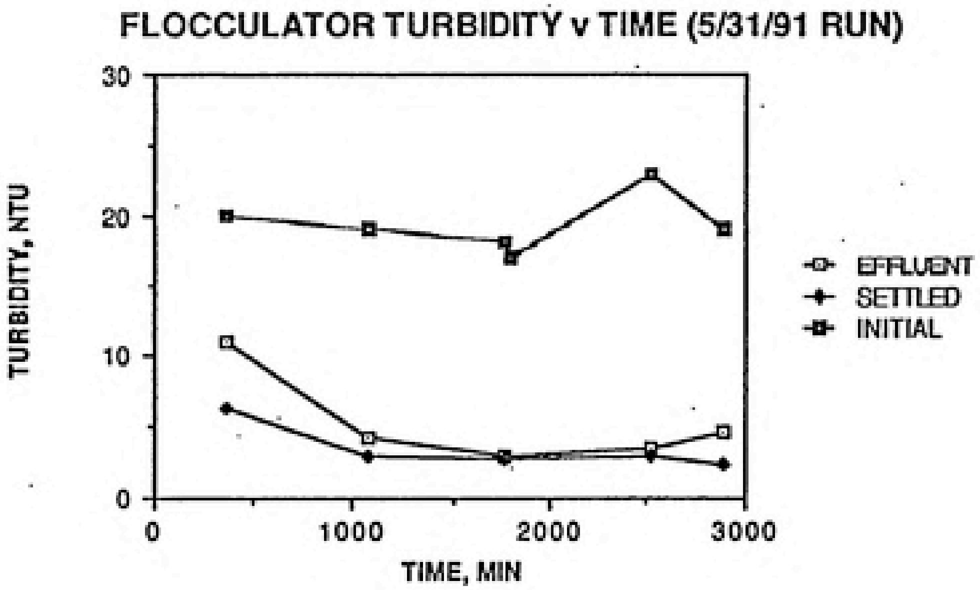
		HEADLOSS:			G-VALUE:			3M MEDIA:		OVERFLOW:			
SAMPLE	TIME	TOP	MID PT	O'ALL	TOP	MID PT	BOTTOM	TURBIDITY,NTU		TURBIDITY,NTU		FEED	INTI
#	min	mm	mm	mm	1/s	1/s	1/s	EFFLUENT	SETTLED	EFFLUENT	SETTLED	SETTLED	TURB
0	360	30	34	35	69.8	18.4	8.9	11.0	6.4	3.7	3.2	0.7	20.0
1	1080	42	45	56	82.6	15.9	29.5	4.2	3.0	2.0	2.0	0.5	19.0
2	1770	63	80	85	101.1	37.9	19.9	3.0	2.8	2.0	1.5	0.8	18.0
3	1800	55	71	76	94.5	36.8	19.9					0.8	17.0
4	2520	82	101	107	115.4	40.1	21.8	3.6	2.9	2.1	2.0	0.8	23.0
5	2895	100	130	135	172.5	68.2	26.9	4.6	2.5	2.0	1.3		
6	2910									2.3	1.7		

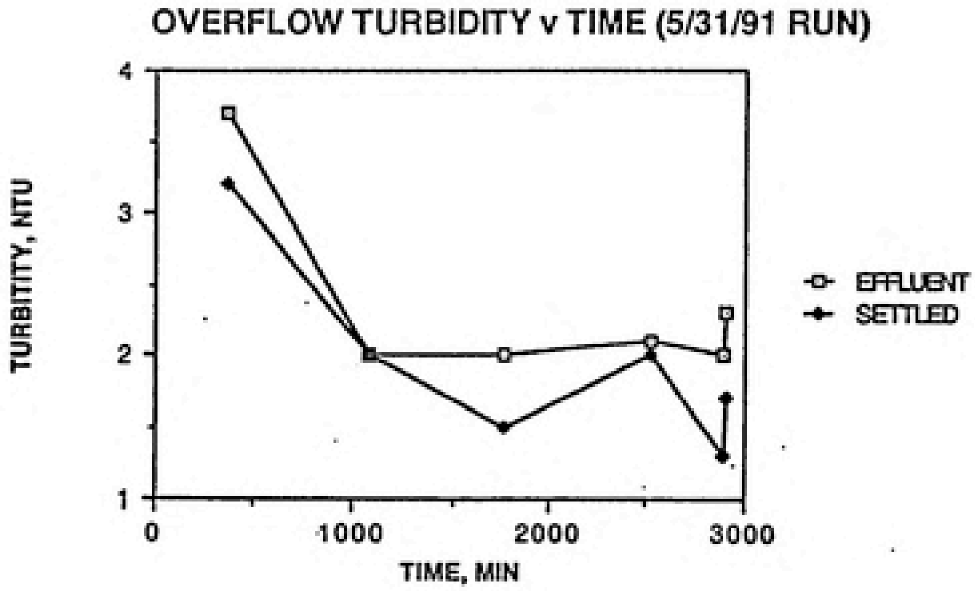
Remarks:

1. This run was to demonstrate performance of flocculator with layered 3M in downflow and Norpak in upflow for 6/3/91 meeting with CDM and EIMCO.
2. The run was suspended for 24 hours after Sample no. 2 to conserve chemicals. The time count ignores this downtime gap.
3. Flow rate at sample nos. 5 & 6 was 9 GPM


HEADLOSS v TIME (5/31/91 RUN)
TEMPORARY SUSPENSION OF RUN
HEADLOSS, mm
TIME, MIN
140
120
100
80
60
40
20
0
1000
2000
3000
TOP
MID POINT
BOTTOM


G VALUE v TIME (5/31/91 RUN)
TEMPORARY SUSPENSION OF RUN
G VALUE, 1/s
TIME, MIN
200
100
0
1000
2000
3000
TOP
MID POINT
BOTTOM


FLOCCULATOR TURBIDITY v TIME (5/31/91 RUN)
TURBIDITY, NTU
30
20
10
0
0
1000
2000
3000
TIME, MIN
EFFLUENT
SETTLED
INITIAL


OVERFLOW TURBIDITY v TIME (5/31/91 RUN)
TURBITITY, NTU
4
3
2
1
0
1000
2000
3000
TIME, MIN
EFFLUENT
SETTLED